THE INFLUENCE OF WAVES ON THE OFFSHORE WIND RESOURCE

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ABSTRACT

The sea surface roughness plays a key role in the momentum exchange process between wind and waves and thus in air-sea interaction in general. For predicting the offshore wind climate it is therefore important to establish and refine models for the description of the sea surface roughness. Aim of the paper is to describe and compare available models of different complexity, which are interesting for wind energy applications. The analysis is confined to conditions of near neutral stability. The models are validated with data from the Rødsand measurement in the Baltic Sea, where a large database of simultaneous wind and wave data is available. Finally they are compared with each other and the measurement in a test application. Significant differences in input requirements as well as accuracy exist between the models. Compared to the simple assumption of a constant sea surface roughness a large improvement can already be achieved with the Charnock relation. A significant further improvement is found for a more complex model that explicitly takes influences of the wave field into account.

KEYWORDS

Wind resource, offshore, air-sea interaction, waves, sea surface roughness, modelling, measurement

1 INTRODUCTION

The favourable wind resource at offshore compared to land sites is caused by the very low surface roughness of the sea. The development of models describing the sea surface roughness is therefore of major importance for offshore wind power utilisation. In contrary to land conditions, the sea surface roughness is not a constant but depends on the waves present. These in turn are governed by the momentum exchange process between wind and waves, which depends on wind speed, water depths and distances from the shore.

The wind resource estimation model WAsP (Mortensen et al., 1993) of the European Wind Atlas (Troen and Petersen, 1989) is the standard method for wind resource estimations on land as well as offshore. WAsP assumes a single value of 0.2 mm for the sea surface roughness. No dependency on wind speed or other parameters is taken into account.

Widely used in meteorological applications is the Charnock model (Charnock, 1955). It works well for open ocean sites, but is problematic in coastal areas since it does not take into account fetch influences. The traditional way of fixing this problem has been to use increasing values of the constant in the Charnock relation when approaching the coast. The physical explanation for the increased roughness of near coastal waters is based on the fact that wind driven waves are most efficient in taking energy out of the mean flow when they are 'young', i.e. in the phase when they are growing rapidly.

A model for the surface roughness of the sea has been developed based on this concept, using an expression for the Charnock constant as a function of wave age (Johnson et al., 1998). Furthermore a simple parameterisation of the sea surface roughness using simple wave data was developed. This model is described in chapter 2.1. Recent data from the Danish offshore measurement at Rødsand include simultaneous wind and wave data. These data are used to validate the wave age dependent model of sea surface roughness. The measurement and data analysis are described in chapter 3. The wave age dependent model for the roughness is compared with the measurements in chapter 4.

Measured wave data are necessary to apply the wave age dependent roughness model. Since these often are not available in practical applications, the empirical relation by (Hasselmann et al., 1973) is used to relate the wave age to fetch (defined as distance to the nearest upwind coastline). This relation is described in chapter 2.2 and compared with the Rødsand measurement in chapter 5. The wave age dependent model and the relation between fetch and wave ages are combined to the fetch dependent model. A comparison with the Rødsand data is reported in chapter 6.

Finally the four models mentioned (constant roughness, Charnock relation, wave age dependent model and fetch dependent model) are tested in their capability to model the wind speed at 10 m height from measured input parameters. A statistical comparison is made using the root mean square error and correlation coefficient between the modelled and measured time series. The results of this test are described in chapter 7.

2 MODELLING SEA SURFACE ROUGHNESS

2.1 Wave age dependent sea surface roughness model

The surface roughness is used to describe the influence of the surface on the vertical wind speed profile. For neutral atmospheric stability it can be written as:

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \qquad (1)$$

where u(z) is the mean wind speed at height z, u_* the wind friction velocity at the surface, κ the von Karman constant and z_0 the surface roughness length.

The surface roughness length for land surfaces is typically in the order of centimetres to meters. For sea surfaces the value is typically below one millimetre. Also, for land surfaces it is usually taken as a constant depending only on the surface, i.e. independent of the wind flow. For water surfaces the roughness length depends on the wave field present, which in turn is dependent on the wind speed and other parameters like fetch, current, water depth, etc.

Describing the sea surface roughness for wind resource studies has the aim to find a simple empirical description for this complex dependency. Furthermore, the description should only depend on parameters usually available in wind resource studies, i.e. preferably not on parameters of the wave field.

Widely used is the description by (Charnock, 1955), relating the sea surface roughness to the friction velocity by means of a single empirical constant:

$$z_0 = z_{ch} \frac{u_*^2}{g} \qquad (2)$$

where g is the gravitational acceleration and z_{ch} the so-called Charnock constant. Experimental studies determined the Charnock constant to approximately 0.011-0.014 for the open sea with fully developed waves. However, the 'constant' frequently has been found to be higher for coastal waters with values of 0.018 or more. Therefore for these situations it is more appropriate to call it the Charnock parameter.

From the point of view of offshore wind power utilisation the uncertainty in the Charnock parameter for coastal waters is unsatisfactory since this is the area most interesting for wind farm development. Many attempts have been made to refine the description of the sea roughness by including additional parameters, which better describe the wave field. Here we employ the approach by (Johnson et al, 1998), which describes the Charnock parameter z_{ch} as a function of wave age c_p/u_*, where c_p is the phase velocity of the dominant wave component:

$$z_{ch} = A\left(\frac{c_p}{u_*}\right)^B \qquad (3)$$

The constants were found to be A=1.89 and B=-1.59. Using (2), the sea surface roughness is calculated as:

$$z_0 = A\left(\frac{c_p}{u_*}\right)^B \frac{u_*^2}{g} \qquad (4)$$

2.2 Fetch dependent sea surface roughness model

The peak wave velocity c_p is usually not available for wind power studies. Therefore a relation is needed to determine the wave age from a more easily available parameter like fetch. (Hasselmann et al, 1973) found the following empirical relation between the dimensionless peak frequency and the dimensionless fetch:

$$\frac{f_p u_{10}}{g} = C\left(\frac{xg}{u_{10}^{2}}\right)^{D} \qquad (5)$$

Here f_p is the peak frequency, x the fetch in metres and u_{10} the wind speed at 10 m height. The constants were found to be C=3.5 and D=-0.33. Using the deep water approximation of the dispersion relation $c^2=g/k$ the peak frequency can be expressed in terms of the peak velocity:

$$f_p = \frac{c_p k_p}{2\pi} = \frac{g}{2\pi c_p} \qquad (6)$$

Together with equation (1) this leads to:

$$\frac{u_*}{c_p} = C \cdot \frac{\kappa}{\ln\left(\frac{10}{z_0}\right)} 2\pi\left(\frac{xg}{u_{10}^{2}}\right)^{D} \qquad (7)$$

We combine equations (1),(4) and (7) to:

$$z_0 = AC^{-B}(2\pi)^{-B}\kappa^{-B-2BD}g^{-BD-1}\left[\ln\left(\frac{10}{z_0}\right)\right]^{B+2BD}\frac{u_*^{2+2BD}}{x^{BD}} = AC^{-B}(2\pi)^{-B}\kappa^{2-B}g^{-BD-1}\left[\ln\left(\frac{10}{z_0}\right)\right]^{B-2}\frac{u_{10}^{2+2BD}}{x^{BD}} \qquad (8)$$

This implicit equation can be used to determine the sea surface roughness solely from u_* and fetch.

3 THE RØDSAND MEASUREMENT

3.1 Site location

A 50 m high meteorological measurement mast has been established at Rødsand in October 1996. It is situated about 11 km south of the coast of Lolland on position (UTM 32) 677642 E, 6047287 N. The location of the mast is shown in Figure 1. Simultaneous wind and wave measurements are performed since April 1998. The measurement is part of a Danish study of wind conditions for proposed offshore wind farms (see: Barthelmie et al., 1999).

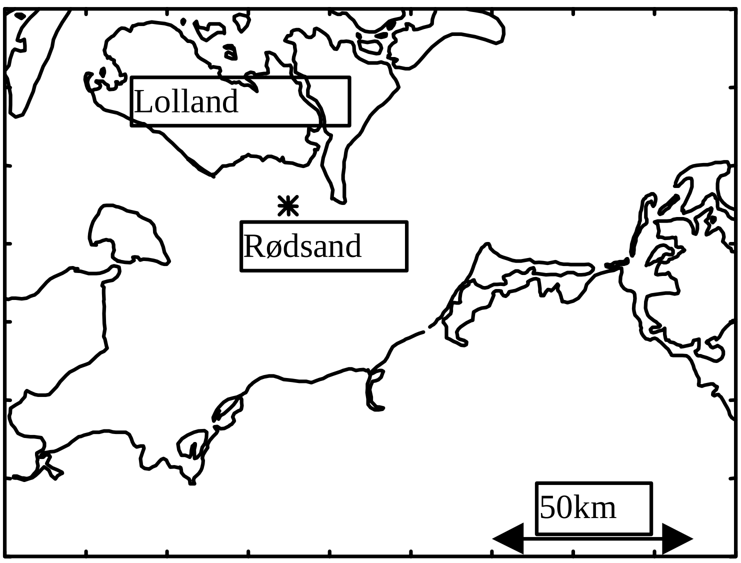

Figure 1: Rødsand measurement site

3.2 Measurements

Table 1 shows the instrumentation of the measurement mast. Wave and current data are collected as well as several atmospheric parameters. About 5900 half-hourly records with simultaneous wind and wave measurements have been used in the analysis.

Table 1: Instrumentation of the Rødsand measurement

	height above mean sea level	instrument	sampling rate
Wind speed	50.3 m	cup anemometer	5 Hz
	29.8 m	cup anemometer	5 Hz
	10.2 m	cup anemometer	5 Hz
Wind direction	29.7 m	wind vane	5 Hz
3 axis wind speed and temperature	46.6 m (42.3 m from 12.5.99)	ultrasonic anemometer	20 Hz
air temperature	10.0 m	Pt 100	30 min mean
Temperature difference	49.8 m – 10.0 m	Pt 500	30 min mean
Sea temperature		Pt 100	30 min mean
Sea level		DHI AWR201 acoustic wave recorder	8 Hz
Sea current		GMI current meter	8 Hz

The mean wind speed was derived from the cup anemometer located at 10m above mean sea level (MSL). The estimated accuracy is about 2%.

The friction velocity u_* was obtained from the Gill ultrasonic anemometer at 46.6m (42.3m from 12/May/99) above MSL. The estimated uncertainty in the resulting value of u* is about 10%, consisting of a measurement uncertainty and a wind direction dependent bias. This bias is due to the flow distortion that transducers and struts cause in the measurement volume. For the horizontal wind speeds a correction for the flow distortions is made internally in the instrument. This is not the case for vertical wind speed, leading to a bias in friction velocity. It depends on the position of the transducers and struts in relation to the flow and is therefore wind direction dependent. Only if the measurements from a large wind direction sector (ideally 120° due to the geometry of the instrument) are averaged the errors are largely cancelled out.

The wave height is measured by an acoustic SODAR-type measurement positioned under water on a support structure near the sea bed. It is located about 100 m south west of the offshore meteorological mast at Rødsand since March 1998. The distance of the instrument to the ground is 3.74 m, the average water level during the measurement was 7.7 m. The distance measured is from the acoustic transducer to the water surface. The cut-off frequency of the instrument is estimated to be 0.8 Hz. The instrument error due to water temperature variations is estimated to be about 3%. In most of the measured time series a small fraction of erroneous data points were found, which were single data points with random values. These were removed by a simple filter. The acoustic wave recorder employs limits for the maximum and minimum water level measured to avoid a contamination with second order echoes. These limits were in some cases too narrow and data, which might be affected by this, were rejected. This was the case for about 1% of the measurements.

3.3 Data analysis

Correction of the wind stress measurement for elevation

For the friction velocity u_* the surface value is needed, while the measured is made with the sonic anemometer at 46.6 m or 42.3 m height. To a first approximation it is usually assumed that the flux in the surface layer is constant, implying that the friction velocity is independent with height. However, this assumption is not entirely correct and for near-neutral and stable conditions the friction velocity increases slightly with height. Since the determination of the sea surface roughness is extremely sensitive for the value of the friction velocity the description by (Panofsky, 1973) has been used to derive the friction velocity at the surface from the one measured at 46.6 m (and later 42.3m) height. With latitude 54 degrees and height 46.6m/42.3m a correction offset of 0.03 m/s has been used.

Correction of all measured wind speeds for flow distortion of the measurement mast

Flow distortions around the mast and the booms on which the instruments are mounted lead to a measurement error. It is obviously very large for situations with direct mast shade. Records for which the anemometers might be in the wind shade of the measuring mast were omitted. This was the case for about 20% of the data. For other wind directions, (Højstrup 1999) gives a method for correcting the measurements of the Vindeby towers. Tower structures and measurement set-up for Vindeby and Rødsand are almost identical and this correction method was applied to the measured wind speeds and friction velocity.

Neutral wind speed

The mean wind speed has been corrected for influences of the atmospheric stability. The atmospheric stability has been described by the Monin-Obukov-length, which is calculated from the sonic measurements and the temperature measurement at 10 m. It is used to derive the neutral wind speed $u_n(z)$:

$$u(z) = \frac{u_*}{\kappa}\ln\left(\frac{z}{z_0}\right) - \frac{u_*}{\kappa}\Psi\left(\tfrac{z}{L}\right) = u_n(z) - \frac{u_*}{\kappa}\Psi\left(\tfrac{z}{L}\right) \qquad (9)$$

The stability function Ψ is calculated after (Geernaert et al. 1986) (cited in Johnson et al., 1998).

The analysis in this paper is confined to near neutral atmospheric stability. The condition of neutral atmospheric stratification is satisfied by correcting the measured wind speed for the influence of stability as described earlier. In addition, this correction is limited to a maximum of 3% correction in u_{10n} and data with larger deviations from neutral stability are omitted. This leads to limits of $-0.5 < z/L < +0.3$ (with z=50m) and excludes about 50% of the measured data.

Sea surface roughness

The sea surface roughness is determined from measurements of the friction velocity u_* and the neutral wind speed at 10 m height $u_n(10)$:

$$z_0 = \frac{z}{\exp\left(\frac{u_n(z)\kappa}{u_{*,s}}\right)} \qquad (10)$$

The von Karman constant κ is taken as 0.4. The dimensionless sea surface roughness or Charnock constant is defined as:

$$z_{ch} = \frac{z_0 g}{u_*^2} = \frac{g z}{u_*^2 \exp\left(\frac{u_n(z)\kappa}{u_{*,s}}\right)} \qquad (11)$$

Peak wave component

To avoid noise problems in determining the velocity of the peak wave component c_p from the wave measurement a method described in (Johnson et al., 1998) is followed. The velocity of the peak wave component has been determined from the measured time series by first calculating the 50% accumulated variance frequency f_{50} and then relating this to the peak frequency f_p by means of a fitted JONSWAP spectrum. The phase velocity of the peak wave component c_p is subsequently calculated from f_p using the linear dispersion relation.

Bandwidth of the wave spectrum

A description of the sea surface roughness from the wave field requires that the measured waves are actually caused by the measured wind and not e.g. stem from an earlier wind condition. For locally generated wind waves in stationary wind conditions the wave spectrum is single peaked. The bandwidth $\log_{10}(f_{75}/f_{25})$ (with f_n =

frequency at n% variance) is used as a criterion for this. Single peaked spectra show a bandwidth close to that of 0.15 found for the fitted JONSWAP spectrum. To ensure that the deviation from this ideal state is limited the data have been selected for their bandwidth. Records with a bandwidth of more than 0.25 have been rejected. This was the case for about 9% of the data.

4 WAVE AGE DEPENDENT SEA SURFACE ROUGHNESS

To validate the approach by (Johnson et al., 1998) (equation 3) the (dimensionless) Charnock constant is plotted versus (dimensionless) wave age in a double logarithmic plot. A linear fit to the data has been made to determine the optimal parameters for this data set. The result is A=2.86 and B=-1.70. The difference to the parameters proposed by (Johnson et al., 1998) is small. The data set described in chapter 3 is plotted in Figure 2 together with results of the wave age dependent model (equation 3) with constants from (Johnson et al., 1998) and with constants fitted to the data.

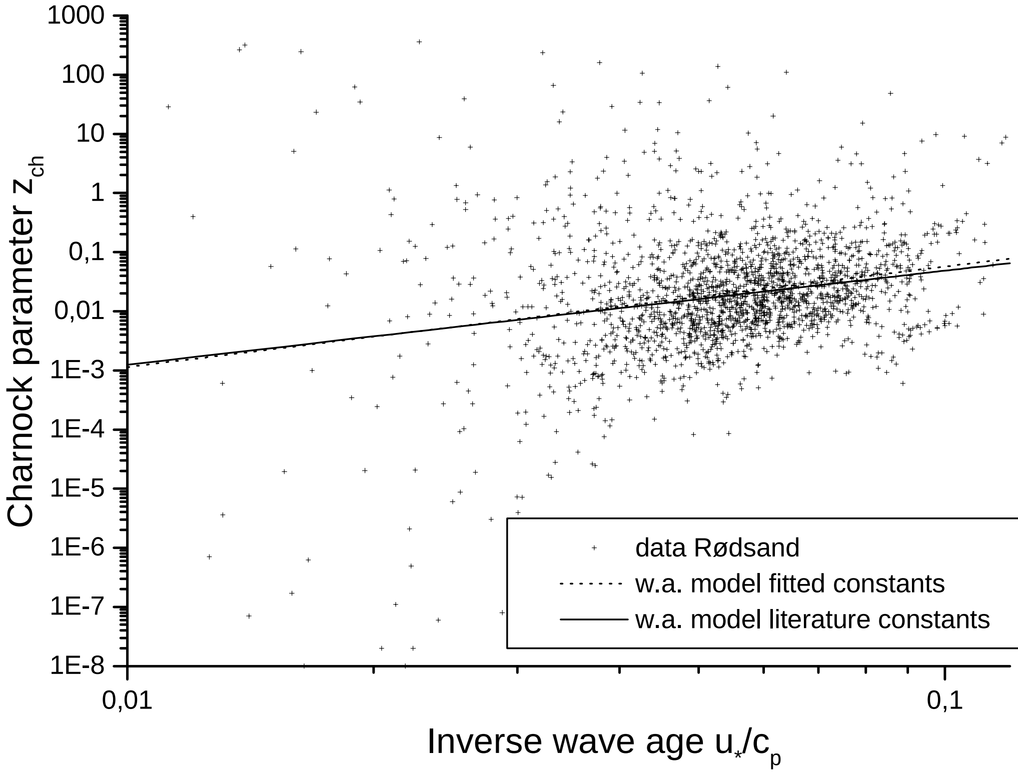

Figure 2: Charnock parameters versus wave age from Rødsand measurement; data from all wind directions are used; lines show the wave age model (equation 3) with constants from literature (Johnson et al., 1998) and with constants fitted to the data

A comparison of measurement and model is difficult since the data show a very large scatter, especially for small inverse wave ages, i.e. old waves. Several problems are encountered for these low values of inverse wave ages:

1. Capillary waves: For low wind speeds capillary waves dominate the sea surface roughness and the functional relation between Charnock constant and inverse wave age is expected to break down. Taking $z_0=0.18T/\rho u_*^2$ (Wu, 1994), with T = surface tension and ρ = water density, the limit between capillary and gravity wave regimes can be estimated to be at a friction velocity of 0.29 m/s.

2. Surface layer height: The measurement of the friction velocity at 45 m height might for shallow boundary layers be above the surface layer. It was estimated that this could be a problem for friction velocities smaller than about 0.2 m/s. Low values of the friction velocity lead to low inverse wave ages and almost all u_*<0.2 m/s belong to an inverse wave age of below 0.04.

3. Measurement uncertainty: For low values of friction velocity and wind speed the measurement uncertainty increases rapidly. Since both quantities are correlated this leads to a large measurement uncertainty for very low inverse wave ages.

For these reason measurements and bin values with inverse wave age below 0.04 are excluded from further analysis. For a comparison with the model the data have been sorted into bins with respect to their inverse wave age. A bin width of 0.01 is used. Thereafter the parameters u_{10n}, u_* and c_p are averaged within each bin. This is done since these parameters are physical quantities and the spreading of the values due to statistical processes can be assumed to approximately follow a normal distribution. This would not be the case for e.g. the sea surface roughness or the Charnock constant. From these averages the bin values of z_{ch} are derived for each bin. The standard deviation of the means of u_{10n} and u_* have been used to estimate a standard deviation of the mean of the bin value of z_{ch}. The result is shown in Figure 3. Also shown is the relation from (Johnson et al., 1998) (equation 3). The agreement is excellent.

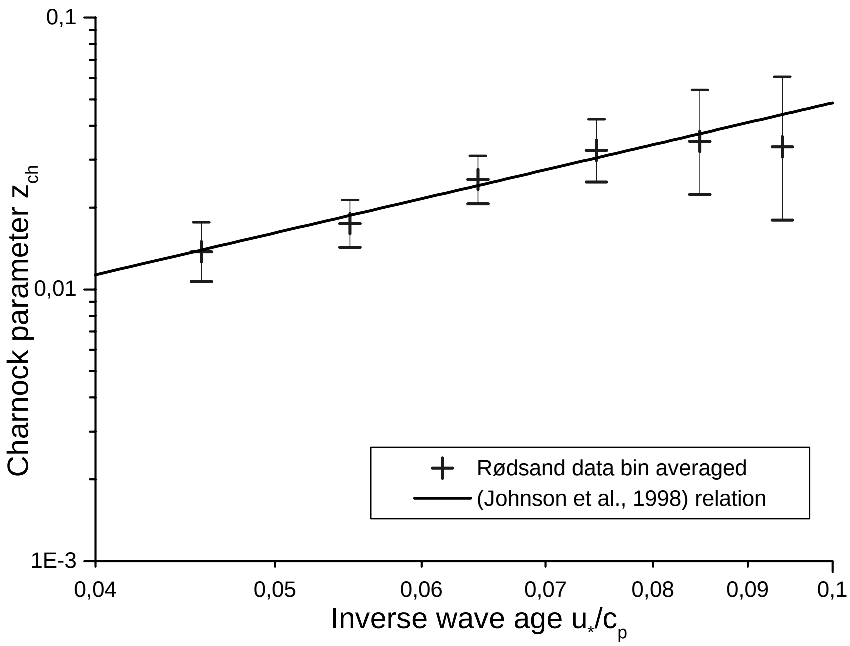

Figure 3: Charnock constant versus wave age from Rødsand data; bin averages with respect to wave age are shown in comparison with the relationship proposed by (Johnson et al., 1998).

5 RELATION BETWEEN FETCH AND WAVE AGE

For the described model of wave age dependent sea surface roughness it is necessary to know the peak wave velocity. This requires wave measurements, which are often not available. One possibility to estimate the wave velocity is to use detailed wave modelling. This, however, is a costly enterprise. Also the reliability of wave modelling in near-shore waters is limited.

A simpler approach is followed here. An empirical description relating the wave age to the distance to fetch has been proposed by (Hasselmann et al., 1973). Their approach is to assume a power law between the dimensionless fetch and the dimensionless peak frequency (equation 5). Figure 4 shows the dimensionless fetch versus dimensionless peak frequency from the Rødsand measurement. It is compared with the relation by (Hasselmann et al., 1973) with their constants and with constants fitted to the data. The fetch has been taken here as the distance to the coastline in wind direction.

The comparison with the original equation by (Hasselmann et al., 1973) (equation 5) shows reasonable agreement. (Hasselmann et al., 1973) found their relation by a fit to data from field as well as wave tank measurements. The field measurements alone show a slightly smaller slope in their plot. A linear fit has been made to optimise the constants for the Rødsand data set. Here also a smaller slope has been found. The result is C=1.68 and D=-0.23. Both relations have been used to model the wave age (see equation 7). The result is shown in Figure 5.

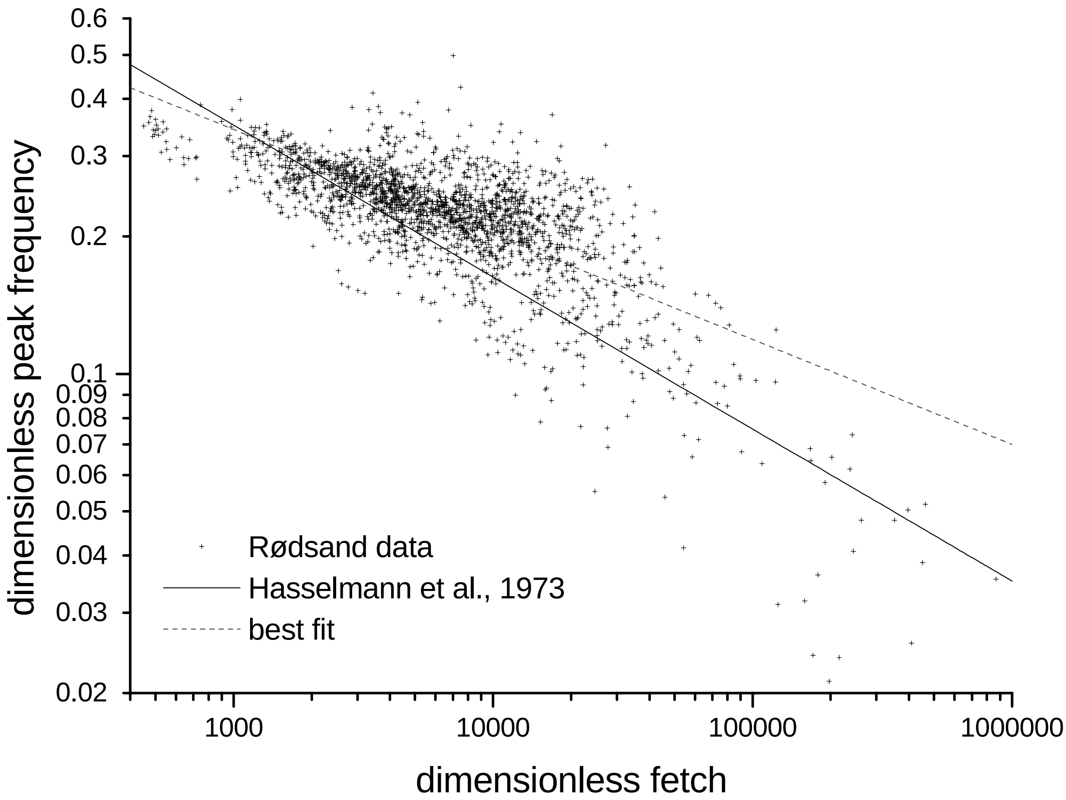

Figure 4: Scatter plot of dimensionless fetch and dimensionless peak frequency from the Rødsand measurement compared with the relation found by (Hasselmann et al., 1973) and with fitted constants

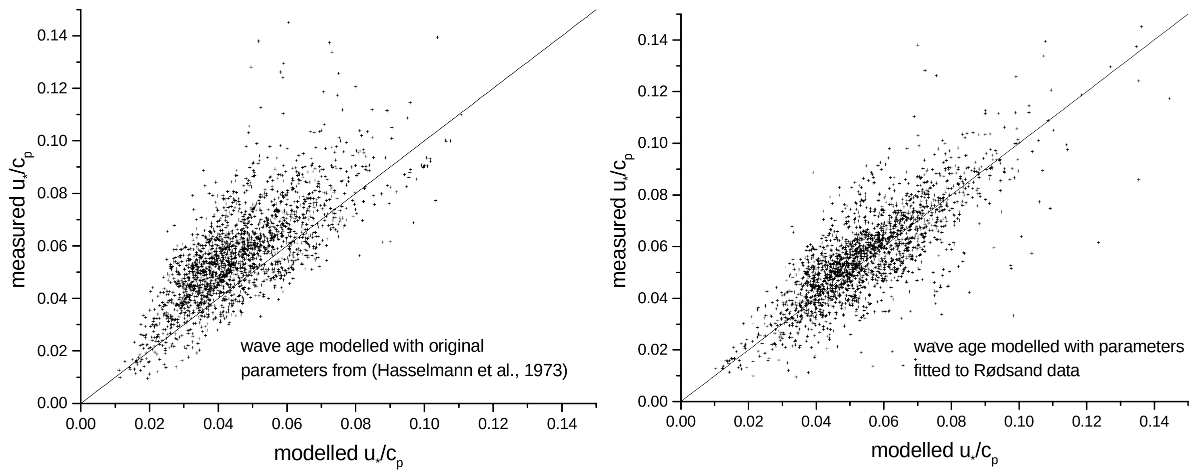

Figure 5: Comparison of measured and modelled wave age values from the Rødsand measurement; the original constants from (Hasselmann et al., 1973) have been used (left) as well as constants fitted to the Rødsand data set (right)

There is a reasonable agreement between modelled and measured wave ages for case of the constants taken from (Hasselmann et al., 1973). However, the agreement is much better for the constants fitted to the data. Both parameterisations will be used and compared in the following to determine the influence of the parameterisation on the results.

6 FETCH DEPENDENT SEA SURFACE ROUGHNESS

The two models of wave age dependent sea surface roughness and fetch dependent wave age can be combined to a fetch dependent sea surface roughness model (see chapter 2.2). This allows to estimate the roughness from wind speed and fetch alone.

This model is only useful if it is able to predict sea surface roughness better than the Charnock model, which only needs wind speed as input and the constant roughness model. These models are compared in Figure 6. For the fetch dependent model results for the two fetches of 10 km and 100 km are shown. Two parameterisations are compared: One where the parameters are taken from literature (Hasselmann et al., 1973), (Johnson et al., 1998) and (Troen and Petersen, 1989) and one with parameters fitted to the Rødsand data set.

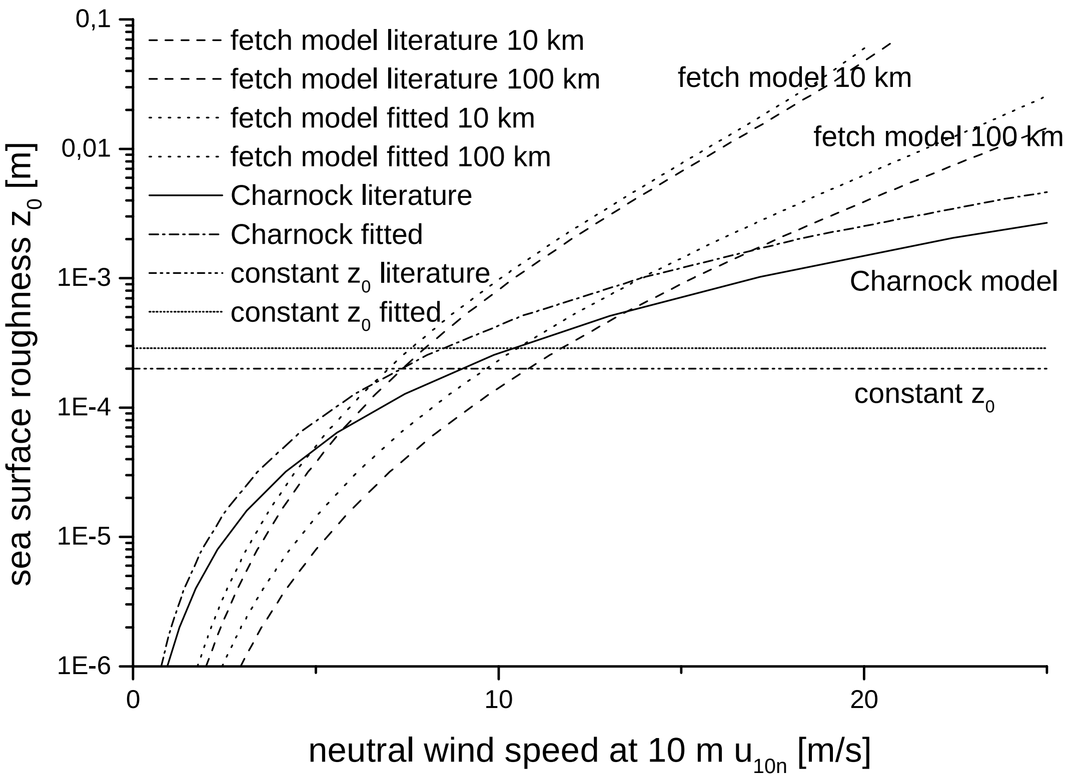

Figure 6: Comparison of different models of sea surface roughness versus neutral wind speed at 10 m height; shown are the constant roughness model, the Charnock model and the fetch dependent model for the two fetches 10 km and 100 km; results are shown for original constants taken from literature as well as for constants fitted to the data set

The difference between the Charnock relation and the fetch dependent formulation is not large, the biggest difference can be found for short fetches and high wind speeds, where the fetch dependent model predicts a higher roughness. Differences between the two different sets of constants are small. For the Charnock relation the fitted (higher) Charnock constant leads to a higher roughness. For the fetch dependent model the fitted parameters also lead to a higher roughness. The difference depends on the fetch and is larger for long fetches. The value of the constant roughness fitted to the measurement is 0.289 mm. This is also higher than the literature value of 0.2 mm. For the most frequent wind speeds between 5 and 10 m/s the difference between the different models is small.

Figure 7 shows the sea surface roughness versus neutral wind speed at 10 m height for the Rødsand data set. The data have been sorted with respect to wind speed, the averages of wind speed and friction velocity have been built and bin values of sea surface roughness have been calculated for each bin from these averages. The data are compared with the Charnock relation, the fetch dependent model and a constant roughness. Parameters from literature have been used for the models. For the fetch dependent model the two extreme fetches of 10 and 100 km are shown. Due to the large range of fetches present in the data, a comparison with this model can be indicative only.

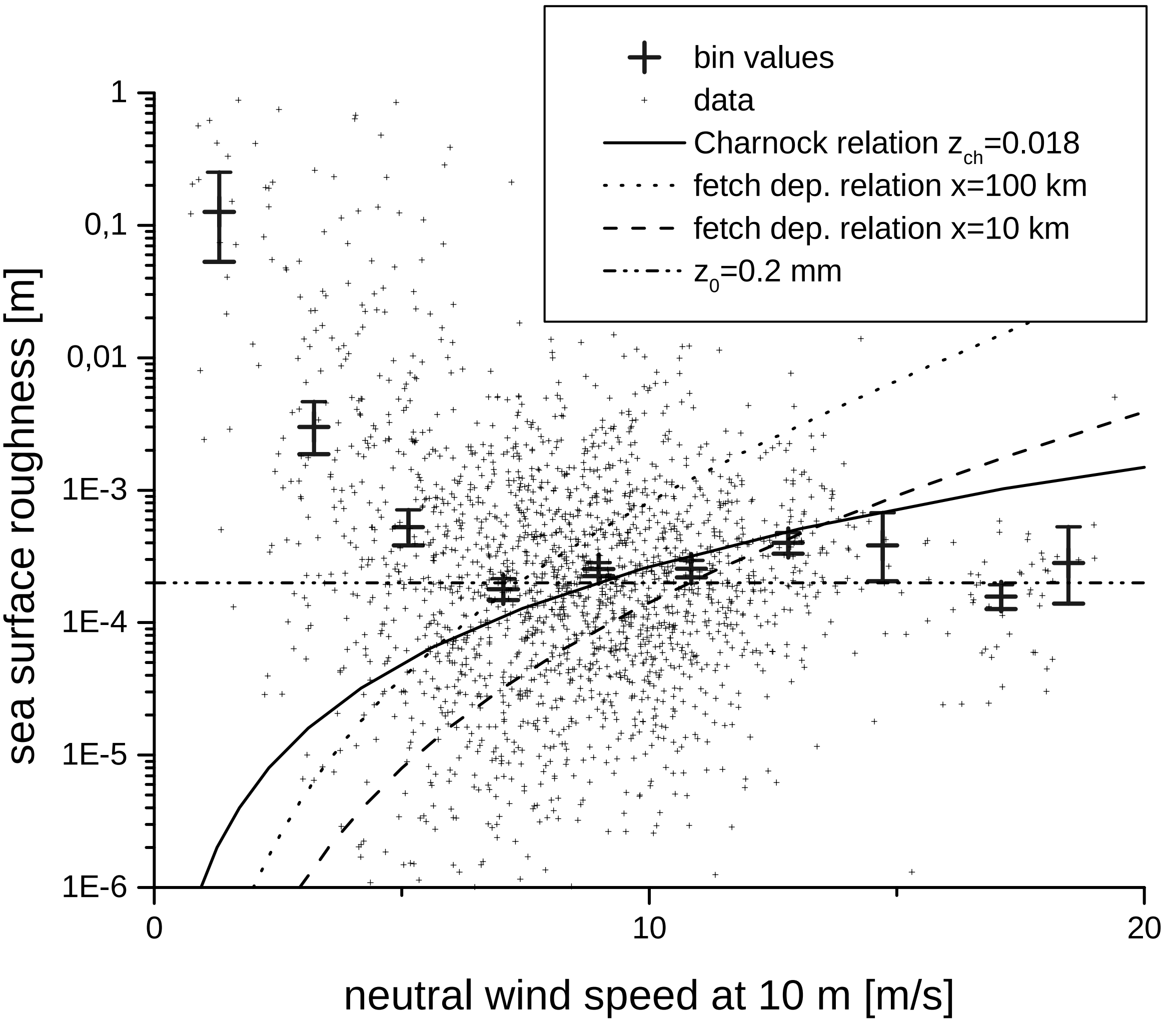

Figure 7: Sea surface roughness versus neutral wind speed at 10 m height from the Rødsand measurement; data, bin values for the data with standard deviation of the mean, Charnock relation, fetch dependent relation and constant roughness model are shown

Generally a large roughness is measured at low wind speeds. At 7 m/s it reaches a minimum. Low wind speeds are connected with low friction velocities, for which the difficulties were already described in chapter 4. Additionally, remaining influences of the atmospheric stability even in the near neutral data might disturb the measurements.

For wind speed bins from 7 to 11 m/s the measured values are very close to the results of all three models. For 13 and 15 m/s the Charnock relation seems to be closest to the measured bin values, while for even higher wind speeds the constant roughness of 0.2 mm is closest. However, only very few data are available for wind speeds above 14 m/s and conclusions can not be based on these few data.

7 TEST OF DIFFERENT MODELS

Due to the large scatter in the measurement data a direct comparison of the different models with the measurement is unsatisfactory. Therefore the models have been used to predict the wind speed at 10 m height from the measured friction velocity and wave speed c_p or fetch. This has been made for each measurement record and the difference between predicted and measured wind speed has been compared statistically by their root mean square error and correlation coefficient r^2. The results are shown in Table 2.

Table 2: Test of different models for sea surface roughness: time series of measured and modelled neutral wind speed at 10 m height are compared by their root mean square error and correlation coefficient; measured parameters are used as input to the models; the constants used in the different models are taken from literature and from a fit to the measured data

model	input para-meters	constants	r^2	rms
WAsP:	-	literature: const=0.2 mm	0.64	2.21
$z_0 = const$	-	Rødsand fit: const=0.289 mm	0.64	2.12
Charnock:	u_*	literature: zch=0.018	0.67	1.81
$z_0 = z_{ch} \frac{{u_*}^2}{g}$	u_*	Rødsand fit: zch=0.0273	0.67	1.77
Johnson et al, 1998:	u_*, c_p	literature: A=1.89 B=-1.59	0.72	1.60
$z_0 = A\left(\frac{c_p}{u_*}\right)^B \frac{{u_*}^2}{g}$	u_*, c_p	Rødsand fit: A=2.86 B=-1.70	0.72	1.59
Johnson et al, 1998 and Hasselmann et al, 1973:	u_*, x	literature: A=1.89 B=-1.59 C=3.5 D=-0.33	0.67	1.75
$z_0 = AC^{-B}(2\pi)^{-B}\kappa^{-B-2BD}g^{-BD-1}\left[\ln\left(\frac{10}{z_0}\right)\right]^{B+2BD}\frac{u_*^{2+2BD}}{x^{BD}}$	u_*, x	Rødsand fit: A=2.86 B=-1.70 C=1.68 D=-0.23	0.67	1.71

The constant roughness model shows the highest rms error of 2.21. Using constants fitted to the Rødsand data decreases the rms error by 4%. Using the simple Charnock relation decreases the rms error by 18% (literature constants) and 20% (fitted constants). The winner of this test is the (Johnson et al, 1998) relation with a decrease of rms error of 28% independent of the set of constants used. However, when no wave measurement is available and the model is extended to a fetch dependent model the decrease reduced to 21% (literature constants) and 23% (fitted data). Generally it can be seen that differences between the models are large compared to differences between different sets of constants from literature and from a fit to the data.

8 CONCLUSION

Aim of the paper is to describe, validate, test and compare models for the sea surface roughness, which might be useable for offshore wind energy applications. The analysis has been confined to the case of near neutral stability and locally generated wind waves and focused on wind speeds above 5 m/s. Four different models have been selected:

1. Constant sea surface roughness: Although obviously a crude simplification this is the most commonly used assumption in wind energy applications. It is used in the wind resource prediction program WAsP (Mortensen et al., 1993).
2. Charnock relation: The Charnock model relates sea surface roughness to friction velocity and in this way describes the change of sea roughness with wind. The ‘constant’ used in the model turns out to be dependent on the location of the measurement. A value of 0.014 for open ocean and 0.018 for coastal areas is usually taken.
3. Wave age dependent model: The fetch dependence of the constant in the Charnock model is caused by differences in the wave fields. One of numerous attempts to describe this dependency is the one by (Johnson et al., 1998), which parameterises the Charnock parameter with wave age.
4. Fetch dependent model: The wave age dependent model can be combined with a description of the dependency of wave age on fetch to yield a fetch dependent model for sea surface. A parameterisation by (Hasselmann et al., 1973) is used to relate wave age to fetch. This model can be used in applications where no wave measurement is available.

Simultaneous wind and wave measurements from the meteorological mast Rødsand in the Danish Baltic Sea have been used to validate and test the models. Two approaches have been followed:

1. A direct comparison of the measured and modelled sea surface roughness or Charnock parameter has been made.
2. The capability of the different models to predict the neutral wind speed at 10 m height from the measured input parameters has been tested and compared statistically.

The following conclusions can be drawn:

1. A comparison of bin averaged values of measured Charnock parameters with values modelled by the wave age dependent model showed an excellent agreement. However, the scatter in the measured data is enormous.
2. A comparison of the empirical relation of fetch dependent wave age with the measurement shows a fair agreement. It is improved by using constants fitted to the measurement instead of literature values.
3. The comparison of the different models with measurement data on the basis of bin averages for wind speeds did not yield a conclusive result. The uncertainty in the measurements is larger than the differences between the different models.
4. As expected from the different complexity of the models the test of wind speed prediction showed significant differences between the models. Compared to the constant roughness model the Charnock relation yields a reduction rms error of about 19%, the wave age dependent model of about 28% and the fetch dependent model of about 22%. As expected, the Charnock relation is an improvement compared to the assumption of a constant roughness. The wave age dependent model again improves the prediction significantly compared to the Charnock model, while the fetch dependent model only yields minor improvements.
5. For each of the models different sets of constants have been compared: the performance with typical constants taken from literature was compared with that using constants fitted to the measurement data. The difference between different sets of constants is small (0-4%) compared to the differences between the models.

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REFERENCES

Barthelmie, R.J., M.S. Courtney, B. Lange, M. Nielsen, A.M. Sempreviva, J. Svenson, F. Olsen and T. Christensen: Offshore wind resources at danish measurement sites. in: 1999 European Wind Energy Conference and Exhibition. 1999. Nice

Charnock, H.: Wind stress over a water surface. in: Quarterly Journal of the Royal Meteorological Society, Vol. 81, pp.639-640, 1955

Donelan, Mark: Air-sea interaction. in: Le Méhauté, Bernard and Daniel M. Hanes (eds.): Ocean Engineering Science Volume 9 Part A. The Sea. 1990. pp.239-292

Geernaert, G.L., K.B. Katsaros and K. Richter: Variation of the drag coefficient and its dependence on sea state. in: Journal of Geophysical Research, Vol.91, pp.7667-7679; 1986

Hasselmann, K., T. P. Barnett, E. Bouws, H. Carlson, D. E. Cartwright, K. Enke, J. A. Ewing, H. Gienapp, D. E. Hasselmann, P. Kruseman, A. Meerburg, P. Müller, D. J. Olbers, K. Richter, W. Sell and H. Walden: Measurements of Wind-Wave Growth and Swell Decay during the Joint North Sea Wave Project (JONSWAP). in: Deutsche Hydrogr. Zeits., Reihe A, Vol. 12, No.8; 1973

Højstrup, J.: Vertical extrapolation of offshore wind profiles. in: proceedings of the 1999 European Wind Energy Conference, Nice, France; 1999

Johnson, H.K., J.Højstrup, H.J.Vested, S.E.Larsen: On the dependence of sea surface roughness on wind waves. in: Journal of Physical Oceanography, Vol.28, pp.1702-1716; 1998

Mortensen, N.G., L.Landberg, I.Troen and E.L.Petersen: Wind Atlas Analysis and Application Program (WAsP). Risø National Laboratory, Roskilde, Denmark. 1993

Panofsky, Hans.A.: Tower Micrometeorology. in: Haugen, Duane A.: Workshop on Micrometeorology. American Meteorological Society 1973

Troen, I., E.L. Petersen: European Wind Atlas. Risø National Laboratory, Roskilde, Denmark. 1989

Wu, J.:The sea surface is aerodynamically rough even under light winds. in: Boundary-Layer Meteorology. Vol.69, pp.149-158; 1994