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Evaluation of the wind resource estimation program WAsP for offshore applications

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ABSTRACT: The increasing interest in harvesting offshore wind energy requires reliable tools for the wind resource estimation at these sites. Most commonly used for wind resource predictions on land as well as offshore is the WAsP program. It has been validated extensively for sites on land and at the coast. However, due to the lack of suitable measurements there is still a need for further validation for offshore sites. Data from ongoing measurements at prospective wind farm sites in the Danish Baltic Sea region are available now. The wind resources estimated from these measurements are compared to WAsP-predictions. They agree well. The only deviation found is for two sites, which are located at about the same distance, but on different sides of the island Lolland. Here the measurements show a difference in the wind resources, which is not predicted by WAsP.

A direction dependent comparison explains this deviation. Wind speed ratios of several pairs of stations are modeled with WAsP for 12 directional sectors and compared with the measurements. Deviations in the directional wind speed predictions were found to correspond with the length of the sea fetch: For smaller sea fetches WAsP seems to slightly over-predict the wind speed, while for long fetches of more than 30 km an under-prediction is found. An analysis of the vertical wind speed profiles at three sites indicates that a combination of different effects is responsible for the correlation between sea fetch and model behavior. Effects of atmospheric stability as well as a fetch dependent sea surface roughness have to be taken into account.

KEYWORDS: Wind resource assessment, WAsP, Offshore wind resource, Coastal sea areas, sea surface roughness, atmospheric stability

1 INTRODUCTION

Suitable sites for wind farms on land are scarce in some regions in Europe, while potential areas for offshore sites are huge. Additionally, the wind resource offshore is much better than on land. Therefore the interest in developing offshore sites for wind energy utilization has been growing in recent years and it is expected that an important part of the future expansion of wind energy utilization at least in Europe will come from offshore sites.

However, compared to land sites the economic viability of offshore wind farms depends on the compensation of the additional installation cost by a higher energy production. A reliable prediction of the wind resource at offshore sites is therefore crucial for project planning and siting.

The wind resource prediction model WAsP [1] of the European Wind Atlas [2] is the standard method for wind resource predictions on land as well as offshore. It has been validated extensively for land conditions. A validation study for coastal stations was performed by inter-comparisons of wind measurements at different heights from high meteorological masts close to the sea [3]. No significant deviation was found. Only very few measurements are available for a validation of WAsP for offshore sites. A comparison with data taken from the Vindeby offshore wind farm showed reasonable agreement with a slight over-prediction of the wind speed at Vindeby [4].

With the new data from offshore masts an evaluation of WAsP is attempted for the use in offshore applications. The aim is to evaluate the limits of applicability of the model. It is not the intention of this study to improve WAsP.

In Denmark plans are going ahead to install 4000 MW offshore wind turbines by the year 2030. In the current planning phase offshore wind measurements are being made at several prospective wind farm sites. Measurements located in the confined Danish waters of the Baltic Sea near the islands of Lolland and Falster at distances of about 10 km from the coast are used to investigate wind characteristics and estimate wind speeds and power productions for planned wind farms [5].

The data presently available from these measurements are used in this study together with data from the Vindeby offshore wind farm, which is located about 2 km from the coast. Thus the measurements cover the distances most likely encountered in the planning of bottom mounted offshore wind farms.

2 WAsP

2.1 The wind resource estimation program WAsP

The Wind Analysis and Application Program WAsP contains models for the vertical extrapolation of wind data taking into account sheltering of obstacles, surface roughness changes and terrain height variations. These models are used twice in the process of predicting the wind resource at a site from wind measurements at a different site. First a regional wind climatology is calculated from a measured time series of wind speed and direction, i.e. wind speed distributions for 12 directional sectors for the geostrophic wind are calculated. It is then assumed that the geostrophic wind climate is representative also for the predicted site. The WAsP models are then used to predict the wind resource for the prediction site from the wind climatology calculated in the first step. The output consists of predictions of Weibull wind speed distributions in 12 directional sectors.

2.2 WAsP for offshore conditions

In comparison to land conditions modeling of the wind resource in coastal waters is complicated by a combination of several effects:

The favorable wind resource offshore is mainly caused by the low surface roughness of water areas. Contrary to land conditions, the sea surface roughness is not constant but depends on the wave field present. This in turn is governed by the momentum exchange process between wind and waves which depends on wind speed, water depths, distance from the shore, atmospheric stability, etc.

For fully developed wind waves the dependence on wind speed can be modeled with the Charnock model [6]. It describes the sea surface roughness as a function of wind speed, but independent of fetch. In the confined waters around the measurement sites the waves are mainly fetch limited and the length of the upwind sea fetch might also be important for the sea surface roughness [7], [8]. In the WAsP model this complex dependency is approximated by an average value of 0.2 mm for the sea surface roughness. No dependency on wind speed or fetch is taken into account. During the development of the WAsP model it was found that the results of this simple approach could not be improved by the use of the Charnock equation [2], but very little offshore data was available for verification at the time.

The atmospheric stability is the second parameter, which differs greatly between land and water areas. The main difference is that on land we see a significant daily variation of stability whereas offshore the large heat capacity of the water dampens out the daily variations to a very low amplitude. Instead we see a quite marked yearly variation, because the temperature of the water lags behind the air temperature. The atmospheric stability has an influence on the vertical momentum transport, which is reflected in the vertical wind speed profile (see e.g. [9]). It also influences the growth of the internal boundary layer after the land-sea roughness change. In the WAsP model the atmospheric stability is taken into account as a perturbation of the logarithmic wind speed profile. The mean vertical heat flux and its variability are used to characterize the atmospheric stability. Land and water surfaces are distinguished by different values for these quantities. An interpolation between land and sea areas is used in a transition zone of 10km on both sides of the coastal discontinuity. Land and water areas are distinguished in the model by their roughness values.

Roughness changes are described by an internal boundary layer (IBL) approach. The IBL model does not depend on the atmospheric stability, i.e. no difference is made between an IBL over land and over water, although it is well-known that stability plays a major role in the development of the IBL (see e.g. [10]).

The model describes the height of the influence of a roughness change by two limits. Below the lower limit the height profile is determined by the new roughness behind the roughness change, above the higher limit is determined by the old roughness and in between the two limits a transitional profile is assumed.

For the measurement stations used here the fetch is between 1.4 and 100 km and the measurement heights between 10m and 50m. The IBL heights versus distance to the roughness change are shown in Figure 1. It can be seen that for offshore stations with a measurement height of 10 m the land influence vanishes at a fetch of 1km in the model. At a measurement height of 50 m this is the case at a fetch of 5km.

This means that roughness changes with a distance to the site of more than 5 km have no influence on the calculations made with WAsP.

A detailed analysis of the influence of the atmospheric stability in the coastal zone has been performed in [11] with the Vindeby data. A comparison with WAsP and a discussion of the performance of the atmospheric stability models of WAsP can be found in [12]. Modifications of the model parameters of WAsP only lead to small improvements in the prediction accuracy. The focus of the investigation here is laid on the question if the length of the upstream sea fetch has an influence on the prediction accuracy of the WAsP model. With the new measurements now available, a wide range of sea fetch distances is available for this investigation.

3 Measurements

3.1 Sites

Measurements are made with several meteorological masts on and around the islands of Lolland and Falster in Denmark. The locations of the sites used here are shown in figures 2 and 3. The coordinates are given in table 1. The measurements at Vindeby sea mast west (SMW), Vindeby sea mast south (SMS), Omø Stålgrunde and Rødsand are measurements from offshore meteorological masts. The measurement at Vindeby land mast (LM) is an accompanying measurement at the coastline. Long term meteorological measurements from the station Tystofte on Sjælland are also used.

The Vindeby masts SMW, SMS and LM are situated near the Vindeby offshore wind farm about 1.5 to 2 km off the north coast of Lolland (Fig. 3). The wind farm consists of 11 Bonus 450 kW turbines. For a detailed description of the wind farm see [13].

The sites Omø Stålgrunde (hereafter abbreviated as Omø) and Rødsand are offshore sites located in the southeastern part of Denmark near the island of Lolland. Both sites have a distance of about 10 km to the nearest land. Omø is located to the north of Lolland near the Vindeby site, while Rødsand is situated southeast of Lolland (Fig. 2).

The meteorological station Tystofte is a land measurement located in the southern part of Sjælland, about 5 km from the coast and 25 km from the Omø measurement site (Fig. 2).

3.2 Instrumentation and data analysis

Wind speeds are measured by cup anemometers at different heights, which are listed in table 1 along with the locations and measurement periods used. All anemometers are mounted on booms and wind direction sectors disturbed by tower shading are also given in table 1. Data from these wind directions have been omitted. All data have been quality controlled by visual inspection of the time series. The estimated accuracy of the wind speed measurement is about 2%. Data logging has been made with 5 Hz sampling rate. All data have been averaged to half hourly mean values.

Wind speed measurements at the Vindeby masts are disturbed for some wind direction sectors by wakes of the turbines of the nearby wind farm. The measured wind speeds are therefore corrected for the shading effect of the turbines when they are bin-averaged for 30º wind direction sectors. Correction factors for the mean wind speeds are estimated with the wind farm modeling program FCalc [14]. Reductions of up to 7% for the SMW and 2% for the LM are predicted.

Figure 5 shows wind roses and wind speed histograms from the 4 measurement stations used.

4 Wind resources

The wind resource, i.e. the long-term mean wind speed, is estimated from the onsite measurements and compared to WAsP-predictions. Deviations between the wind resource during the measurement period and the long-term average were corrected by correlation with the 14 year long time series from the station Tystofte. The estimation of the long term mean wind speeds from the measurements was done by a combination of different methods using all available measurements (see [5]).

It has to be kept in mind, however, that the measurements at Omø and Rødsand run intermittently with a total data set equivalent to only about 8 and 12 months, respectively. Even though they were corrected, this leaves some uncertainty of the estimated mean wind speeds. The uncertainty in the estimated long term average wind speed was judged to be +/- 5% for Omø and Rødsand and +/-2% for the other stations.

All stations are located either offshore or in very flat terrain. Height variations could therefore be neglected. Also, for none of the measurement sites a correction due to obstacles was necessary. Therefore only the roughness model has been used in this study. A roughness map with a simple roughness classification has been made for large areas surrounding the measurement sites. Three roughness classes are distinguished: water areas with roughness 0.0002m, predominantly agricultural areas with roughness 0.05m and woods and cities with roughness 0.4m. As an example the roughness map of the Vindeby site is shown in figure 4.

WAsP estimations were calculated using two different measurement stations as input:

- The Vindeby land mast, which is a coastal measurement at the Vindeby site. The predictions made with these measurements were corrected for deviations from the long-term average.
- The Tystofte station, which is a long term land measurement.

Figure 6 shows the mean wind speeds of the sites versus their distances to the nearest coast, i.e. their minimum fetches. The points connected with lines are WAsP predictions; the squares are the estimations from the onsite measurements. The error bars indicate the estimated maximum uncertainties of the wind resource estimated from the measurements.

Deviations of the WAsP predictions from the estimations based on the onsite measurements are generally small, up to 5%. They are in the same range as the uncertainties in the wind speed estimations based on the onsite data. As expected, the mean wind speed rises with increasing distance to the coast. The largest increase in wind speed when going offshore from the coast is found for the first kilometers. The increase in wind speed between the coastal station (Vindeby LM) and the offshore sites in 10 km distance is about 10-15%.

For comparison WAsP predictions have also been made for conditions far away from any land. They are shown as additional points at maximum fetch in figure 6. It can be seen that WAsP predicts only a very small influence of land for distances larger than about 10 km. The two sites Rødsand and Omø already almost reach that limit.

The WAsP predictions based on the coastal and the land measurements coincide at the site of the coastal station. For stations further away from the coast the predictions differ up to about 3% with the prediction based on the land measurement being lower than that based on the coastal measurement. For sites near the shore both predictions are very close to the measurement. Differences are only 1-2% and lie within the uncertainty range of the measured data. For the sites Omø and Rødsand, which have larger distances to the shore, the differences are still small (1-5%). However, a difference between these two sites is found in the measurements while WAsP predicts almost equal values.

5 Influence of the sea fetch

5.1 Methodology

The WAsP method uses measurements from one site (predictor) to estimate the wind resource at the predicted site. Within the model the measured directional wind speed distributions are described by Weibull functions. For short time series this procedure introduces an error due to deviations of the measured distribution from Weibull curves. To avoid this error the comparison is made for wind speed ratios rather than wind speeds. In this way the results are also largely insensitive to other wind direction dependent properties like the atmospheric stability, since such influences would be present at both stations under investigation.

Ratios of measured wind speeds from two different stations are made for 12 wind directional sectors. These are compared with the respective ratios from WAsP estimated wind speeds. With different fetches for the two stations the influence of the sea fetch can be investigated in its measured and modeled influence on the wind speed.

An example of the directional dependence of the wind speed ratio is given in figure 7. The ratio is obtained by dividing the measured mean wind speed of Vindeby SMW by that measured at Vindeby LM. It is plotted versus the wind direction measured at Vindeby SMW. No corrections for wind farm shading have been applied here and the directional resolution is 3º.

The directions with mast shading are shown and the disturbance can clearly be seen. Also indicated are the directions of the 11 turbines from the Vindeby wind farm. The reduction of the wind speed due to the influence of the wakes can be identified.

For the WAsP estimations of the wind speed ratios a common time series of wind speeds and directions is compiled for both stations. The measured data of one site are taken as input to WAsP to derive a wind climatology of the station itself and of the second measurement station. This is used to predict the sector-wise mean wind speeds for both sites. Subsequently the predictor and predicted station are exchanged and a new ratio calculated. The average ratio is used for comparison with the measurement (see figures 8 to 10). Differences between the two ratios were found to be negligible (<0.8%).

The ratios of the measured data are derived from the same time series as used for the WAsP predictions. The wind speeds of both stations are bin averaged in 30° bins with respect to the wind speed of one station. This is repeated with the wind direction of the other station and the average ratio is used for comparison. Wind direction sectors where the measurement is disturbed by mast interference are omitted. Uncertainties of the measured ratios are estimated as the average standard deviation of the means plus half of the difference of the two ratios calculated.

5.2 Direction dependent wind speed ratios

Examples for measured and WAsP estimated direction dependent wind speed ratios are shown in figures 8, 9 and 10 along with the lengths of the sea fetches of the respective stations. The solid lines show the measured ratios and the dashed lines are WAsP predictions. Measured data with possible mast interference have been omitted.

Figure 8 shows the ratios of Vindeby SMW and LM. Vindeby SMW is located 1.6 km off the north coast of Lolland (Fig. 3). Here the behavior of WAsP for small fetches can be investigated.

The measurements show two distinct maxima of the ratio, in directions which are roughly along the coastline. This situation leads to a large fetch difference since the SMW has long sea fetches while the LM has mainly land fetch. In between these maxima (sectors 120º-180º) SMW has a short sea fetch of only 1.4 to 3 km. For the other directions both stations have similar long sea fetches and the ratio is close to one.

The WAsP-predictions show generally the same directional pattern as the measurements. In most cases the deviations between measurements and WAsP-predictions are small and the general behavior of the directional wind speed difference between the two stations is modeled well. Significant deviations are found only for the case with land fetch for LM and short sea fetch for SMW where WAsP seems to over-predict the difference between the wind speeds on land and at sea.

Figure 9 shows the results for the ratio between Omø and Vindeby LM. The overall situation at these sites is quite similar to the one for Vindeby SMW and LM, only that Omø is located about 10 km further offshore (Fig. 3). 150° and 180° are the sectors with wind from Lolland and a sea fetch of about 10-15 km. Here WAsP again over-predicts the difference between sea and land. The very rapid change of sea fetch length from 15 to more than 80 km at 200º seems to have an influence also on the wind direction sector 180º. For the very long fetches at Omø at 120º and to a lesser extent at 210º and 240º WAsP under-predicts the difference.

In figure 10 the ratios of the two offshore stations Omø and Rødsand are shown. Rødsand is located 11 km off the south coast of Lolland and the two sites are about 60 km apart from each other (Fig. 2). A comparison of these sites gives the opportunity to study the measured and predicted differences for two offshore stations with very different fetches situations. The measurements show a minimum in the ratios at wind direction sectors 270º and 300º and a maximum at 330º. This corresponds closely to the very large sea fetches at Rødsand in directions 260º to 290º and at Omø at 330º to 350º. For the other directions the ratio does not deviate much from one.

The WAsP-predictions show only very small deviations from unity. This leads to significant deviations of 6-12% from the measurements for the two cases mentioned. For the 30º sector a smaller deviation can be seen which can not easily be assigned to a fetch difference. For all other wind directions the deviations are in the order of the measurement uncertainty.

6 Wind speed profiles

To investigate possible causes for the deviations of the WAsP model measured and modeled vertical wind speed profiles are compared. Two pairs of stations have been used: Vindeby LM and SMW as well as Vindeby LM and Omø. Measurements are available at three heights: 10m, 30m and 50m (46m at LM, 48m at SMW). The wind speed measurements have been corrected for the effect of flow distortion caused by the measurement towers. The correction has been made with a procedure developed for the Vindeby towers (see [15]). Data for wind directions where the tower was upwind of the anemometer were omitted.

WAsP calculations are made with the measured time series at Vindeby SMW at 48m and Omø at 50m height as input. Estimations are made for both sites at all heights.

In most cases WAsP predictions of the mean wind speeds as well as estimations of vertical wind speed profiles agree well with the measurements. Some examples of measured and modeled profiles are shown in figures 11 and 12.

Figure 11 shows the case with wind blowing from land, i.e. Vindeby LM has land fetch, Vindeby SMW has about 1.6 km sea fetch and Omø has about 10 km sea fetch.

The earlier comparison of the wind speed ratios showed that WAsP over-predicts the difference between LM and the offshore masts at 50 m height (Figs 8, 9). This is repeated in the profiles shown in figure 11.

The profiles for the offshore stations are steeper (larger slope) than for the LM due to the difference in land and sea roughness. A comparison of the profiles from Vindeby SMW and LM clearly shows a wind speed difference that decreases with height. At the highest anemometer at 48 m the difference is only about 3%. This shows that at 1.6 km distance the influence of the land is still dominant at this height.

Comparing the wind speed profiles of Vindeby LM and Omø the same tendency can be seen, though to a lesser extent. As expected, the wind speed difference at the highest anemometer is larger than for the SMW, which shows that the internal boundary layer from the land-sea transition is higher and the wind is much less influenced by the land roughness.

Comparing the shape of the profiles, it can be seen that the WAsP-calculated profiles differ in steepness as well as curvature from the measured ones. This can also be seen in Figure 12, which shows the situation of land fetch for the LM and long sea fetches for both of the offshore masts (240º sector).

7 Sensitivity analysis

For WAsP calculations only the measured data and roughness maps are needed as input. The roughness maps have to be made by estimating the roughness of the terrain. This roughness classification is to some extent subjective. Since different roughness estimates will have an influence on the calculations it is important to make a sensitivity study. The aim is to investigate if a different roughness estimation also qualitatively changes the results found.

Example calculations of direction dependent wind speed ratios and profiles have been made using different roughness maps. Two extreme roughness maps with very high and with very low – but still not completely unrealistic – roughness values for land areas have been prepared. The results of the WAsP calculation with these maps are compared with the results obtained with the original maps. The roughness length of water can not be changed in the WAsP model since here the value (0.0) is used as an indicator not only for the roughness (which is fixed as 0.2mm), but also for the heat fluxes over water.

For the wind direction dependent wind speed ratios the case of Vindeby LM and Vindeby SMW has been chosen as example. The roughness estimations for the two extreme roughness maps are shown in table 2. The result of the calculations are shown in figure 13.

The WAsP-predictions with all three maps show generally the same directional pattern. The significant deviations from the measurements found with the original maps for the land sectors (150°-210°) are also present for the calculations using the high and low roughness maps. The conclusion that WAsP seems to over-predict the difference between the wind speeds on land and at sea is qualitatively not questioned by a variation in roughness within the limits shown in table 2. However, the choice of roughness has of course an influence on the magnitude of the over-prediction.

For the comparison of wind profiles the case of Omø Stålgrunde and Vindeby LM with wind from land (150° and 180°) has been chosen (see figure 14). For the wind profile calculations a detailed map around the Vindeby stations was used. The roughness in this map has been changed as shown in table 3.

It can be seen that the variation in roughness has a large influence on the calculations for Vindeby LM , while Omø Stålgrunde is not influenced. This reflects the fact that WAsP is not influenced by roughness changes at such large distances from land (>10km for Omø Stålgrunde).

Comparing the different WAsP-calculated profiles of the Vindeby LM with the measured one reveals again that the wind speed quantitatively is influenced by the choice of roughness. However, the deviations both in steepness and curvature between measured and calculated profile do not depend on the choice of roughness map.

8 Conclusion

The data presently available from ongoing measurements in the Danish Baltic Sea have been analyzed and compared with predictions made with the wind resource estimation program WAsP. Measurements of a coastal and an inland station have been used for the predictions. It was found that the predictions of the long-term average wind resource are in good agreement with measurements.

The measurement indicates a small difference in wind resources between the stations Rødsand and Omø, which is not predicted by WAsP. A possible reason for this is the difference in the fetch situation. Omø is surrounded by land about 10 km distance to the south, west and northeast directions, while Rødsand has land at this distance only in the northern and north-eastern directions. The probability of wind from this direction is low (Fig. 5). It also has long sea fetches in the most frequent westerly wind directions (Fig. 2).

A direction dependent comparison of measured and predicted wind speeds allows comparisons between the different fetch situations. The investigation of the direction dependent wind speed also shows a generally good agreement between WAsP-predictions and measurements. However, for single wind directions significant deviations were found. These deviations show some correlation with the length of the upwind sea fetch. WAsP tends to over-predict the wind speed for situations with short sea fetches and under-predict it for long fetches. This effect explains the measured differences between the Omø and Rødsand sites. The very long fetches at Rødsand, which also occur in the prevailing wind direction lead to higher wind speeds compared to Omø. Since WAsP does not take these long fetches into account it under-predicts the wind resource at Rødsand. Fetches of more than 10 km (transition around coastal discontinuity) have no influence on the calculations (see chapter 2.2).

The comparison of measured and predicted height profiles shows deviations between modeled and measured profiles both in steepness and in curvature. This indicates that a combination of different causes is responsible for the deviations found for some wind directions. The modeled sea surface roughness can not solely be held responsible for the deviations. The growth of the internal boundary layer and the influence of the atmospheric stability also seem to play an important role.

In a sensitivity analysis WAsP results were tested for the dependency on the estimation of the terrain roughness description. Comparative calculations were performed for two examples with extremely high and low roughness estimates. For the direction dependent wind speed ratios as well as the wind profiles quantitative differences were found, but the qualitative result is not affected.

A detailed model is needed to find an explanation for these findings. It might have to include several effects like the dependence of the sea surface roughness on wind speed and fetch (see e.g. [8]) as well as the influence of the atmospheric stability on the height profile of the wind speed and on internal boundary layers due to roughness changes (see e.g. [4]).

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Table captures:

Table 1: Location, time, heights of the measurements and influence of tower shade (the anemometer heights used in this study are marked with *)

Table 2: Roughness estimates for the sensitivity analysis of WAsP results on roughness map for wind speed ratio

Table 3: Roughness estimates for the sensitivity analysis of WAsP results on roughness map for wind profiles

Figure captions:

Figure 1: Height of IBL behind a roughness change versus the distance to that change as modeled by WAsP

Figure 2: Locations of the measurement sites in the Baltic Sea in the southern part of Denmark

Figure 3: Layout of the Vindeby offshore wind farm and the measurement masts Vindeby SMW, SMS and LM.

Figure 4: Map of roughness change lines abound the Vindeby site; the distance between the grid lines is 10km; different colors indicate the different roughness lengths used (0m for water, 0.05m for agricultural areas and 0,4m for cities and forests

Figure 5: Wind roses and wind speed histograms (with fitted Weibull distributions) for (from top): Rødsand, Omø Stålgrunde, Vindeby SMW and Vindeby LM

Figure 6: Long term mean wind speeds for a coastal and 4 offshore sites at 48 m height estimated from onsite measurements and predicted by WAsP on the basis of a coastal and a land measurement; additional points are shown (at maximum fetch) for WAsP predictions far offshore

Figure 7: Measured ratios of mean wind speed Vindeby SMW / Vindeby LM; directional resolution 3º; directions of the turbines and measurement masts are shown with arrows

Figure 8: Vindeby SMW / Vindeby LM: Measured and WAsP-predicted wind speed ratios (top) and sea fetches (bottom) versus wind direction

Figure 9: Measured and WAsP-predicted wind speed ratios versus wind direction from Omø / Vindeby LM (top) and sea fetches of Omø and Vindeby LM versus wind direction

Figure 10: Omø / Rødsand: Measured and WAsP-predicted wind speed ratios (top) and sea fetches (bottom) versus wind direction

Figure 11: Measured and WAsP-predicted mean wind speeds for wind directions with land fetch situations (150° and 180° sectors) versus measurement heights (in logarithmic scale) for the two sites Vindeby LM and SMW (upper graph) and Vindeby LM and Omø (lower graph); the error bars show the 2% estimated uncertainty in the wind speed measurement

Figure 12: Measured and WAsP-predicted mean wind speeds for wind directions with different fetch situations (240° sector) versus measurement heights (in logarithmic scale) for the two sites Vindeby LM and SMW (upper graph) and Vindeby LM and Omø (lower graph); the error bars show the 2% estimated uncertainty in the wind speed measurement

Figure 13: Sensitivity analysis: Measured and WAsP-predicted wind speed ratios versus wind direction from Omø / Vindeby LM; the calculations with WAsP were made with the original roughness description and two extreme high and low roughness estimates

Figure 14: Sensitivity analysis: Measured and WAsP-predicted mean wind speeds for wind directions with land fetch situations (150° and 180° sectors) versus measurement heights (in logarithmic scale) for the two sites Vindeby LM and Omø; the error bars

show the WAsP calculations with the two extreme high and low roughness estimates; measurement uncertainties are not shown here

Table 1: Location, time, heights of the measurements and influence of tower shade (the anemometer heights used in this study are marked with *)

Site	Location (UTM-32)	Time period of measurement	Height of anemometers	Sectors with tower shade
Vindeby SMW	636179 m E 6093319 m N	11/93 - 5/96	7, 20, 38, 48*	30, 60
		9/96 – 8/98	10*, 30*, 48*	30, 60
Vindeby LM	636793 m E 6091717 m N	5/93 - 5/96	7, 20, 38, 46*	150, 180
		9/96 – 9/98	10*,30*,46*	330, 0
Omø	636080 m E 6102600 m N	8/96 – 8/98	10*, 30*, 50*	90
Rødsand	677900 m E 6048300 m N	10/96 – 5/98	10*, 30*, 50*	60, 90

Table 2: Roughness estimates for the sensitivity analysis of WAsP results on roughness map for wind speed ratio

original roughness lengths	low estimate	high estimate
0	0	0
0.05	0.03	0.1
0.4	0.2	0.5

Table 3: Roughness estimates for the sensitivity analysis of WAsP results on roughness map for wind profiles

original roughness lengths	low estimate	high estimate
0	0	0
0.01	0.005	0.02
0.05	0.03	0.1
0.1	0.05	0.15
0.15	0.1	0.25
0.25	0.15	0.3
0.3	0.2	0.5

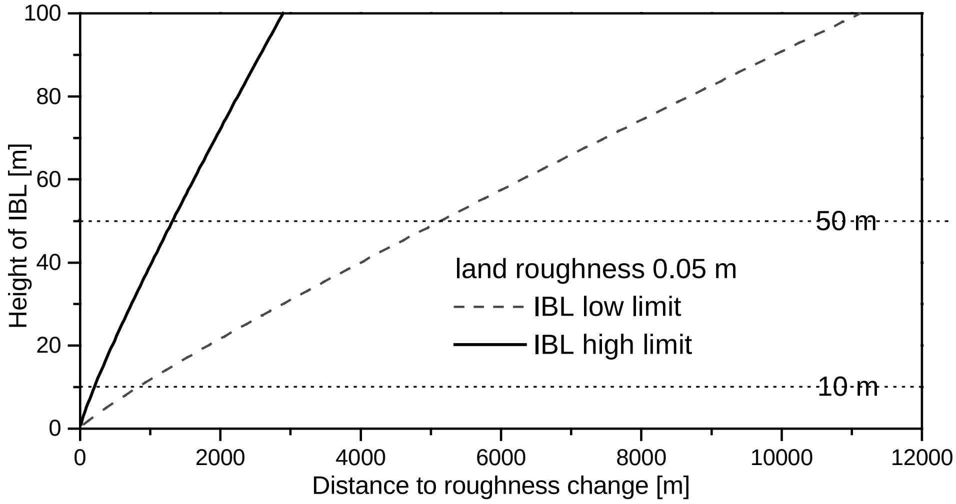


Figure 1: Height of IBL behind a roughness change versus the distance to that change as modeled by WAsP

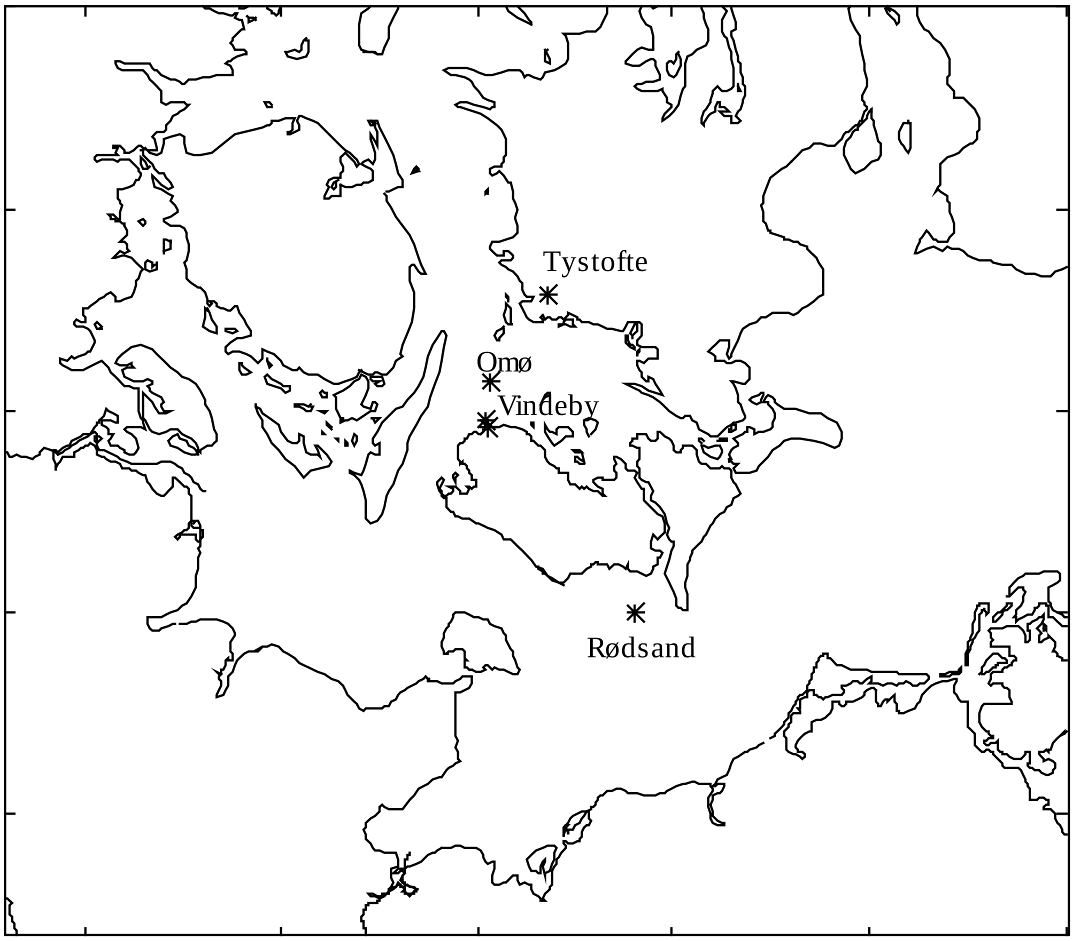


Figure 2: Locations of the measurement sites in the Baltic Sea in the southern part of Denmark

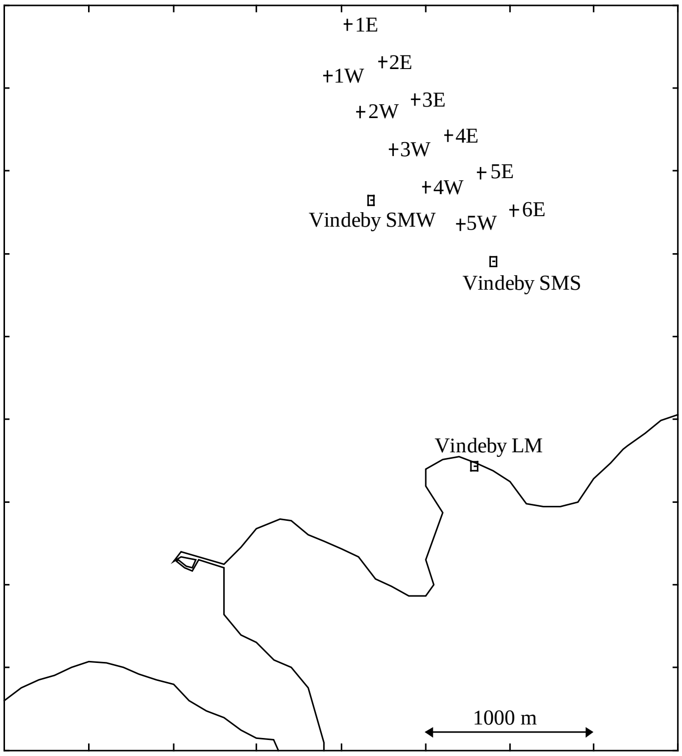


Figure 3: Layout of the Vindeby offshore wind farm and the measurement masts Vindeby SMW, SMS and LM.

Figure 4: Map of roughness change lines abound the Vindeby and Omø Stålgrunde sites; the distance between the grid lines is 10km; roughness values used: 0.0m for water, 0.05m for agricultural areas and 0,4m for cities and forests

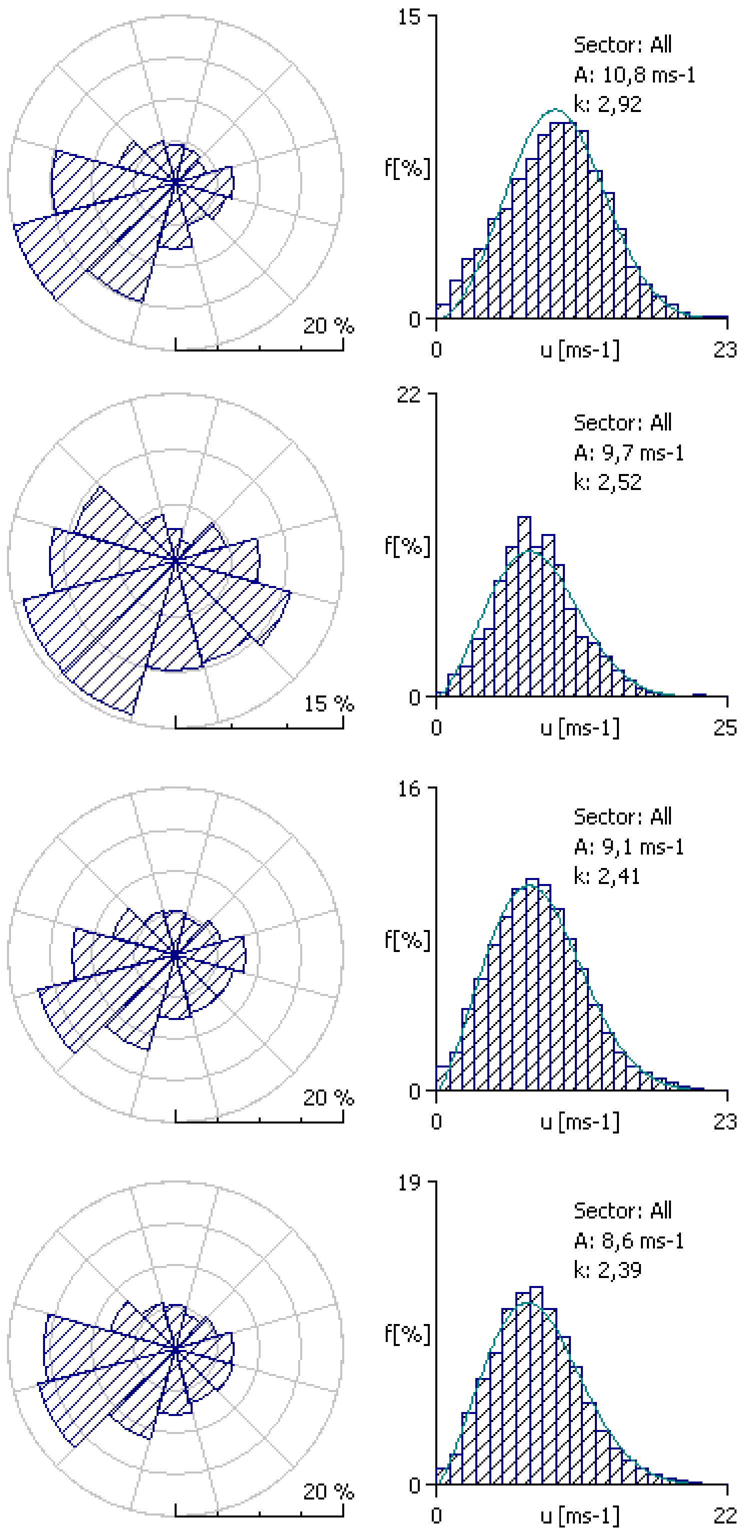


Figure 5: Wind roses and wind speed histograms (with fitted Weibull distributions) for (from top): Rødsand, Omø Stålgrunde, Vindeby SMW and Vindeby LM

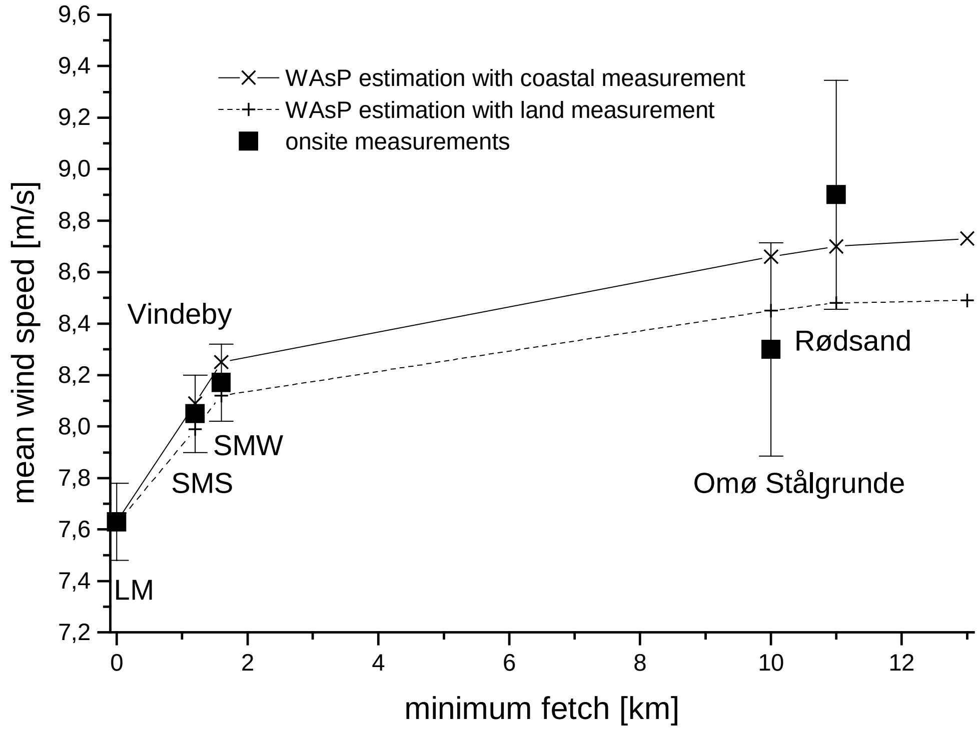


Figure 6: Long term mean wind speeds for a coastal and 4 offshore sites at 48 m height estimated from onsite measurements and predicted by WAsP on the basis of a coastal and a land measurement; additional points are shown (at maximum fetch) for WAsP predictions far offshore

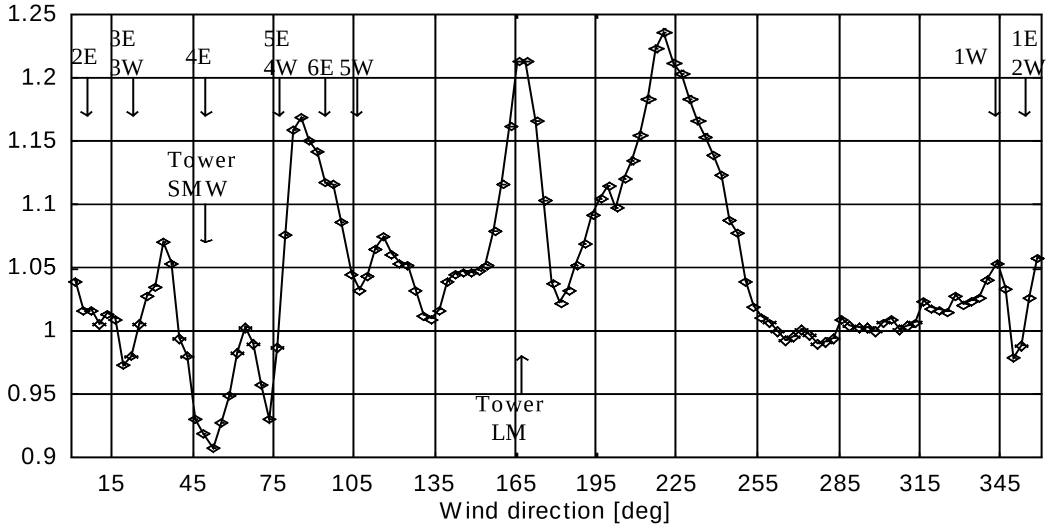


Figure 7: Measured ratios of mean wind speed Vindeby SMW / Vindeby LM; directional resolution 3º; directions of the turbines and measurement masts are shown with arrows

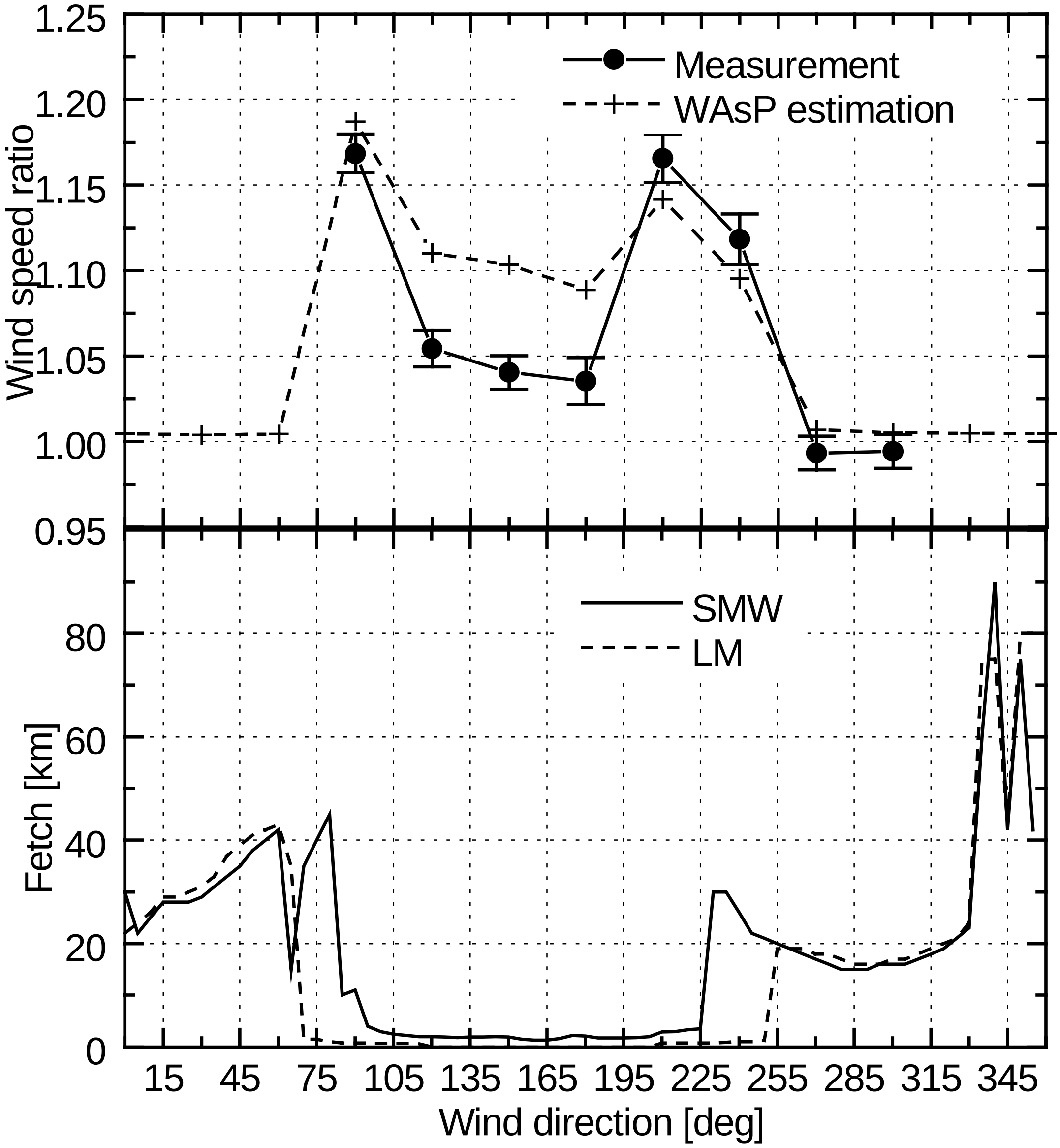


Figure 8: Vindeby SMW / Vindeby LM: Measured and WAsP-predicted wind speed ratios (top) and sea fetches (bottom) versus wind direction

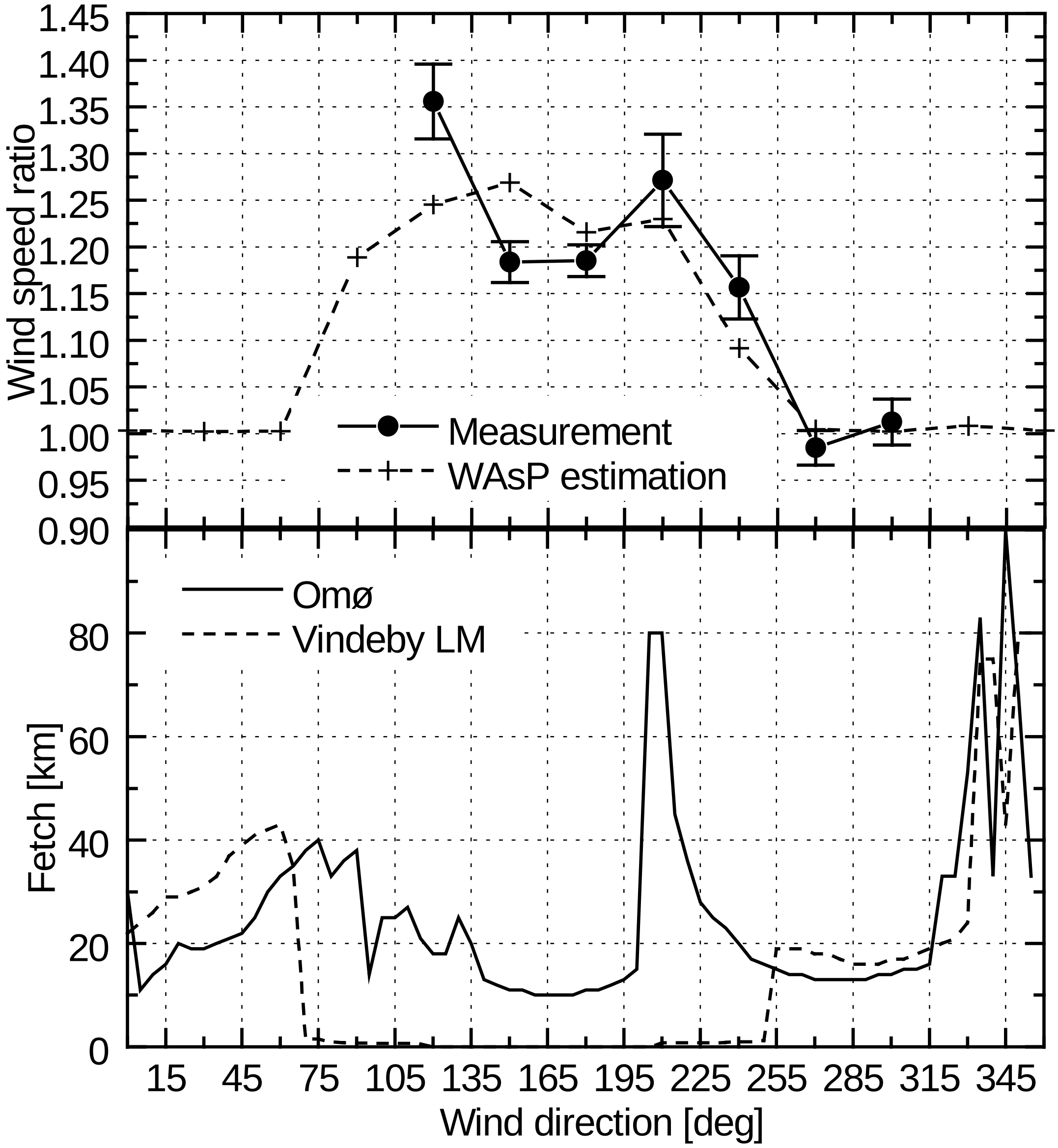


Figure 9: Measured and WAsP-predicted wind speed ratios versus wind direction from Omø / Vindeby LM (top) and sea fetches of Omø and Vindeby LM versus wind direction

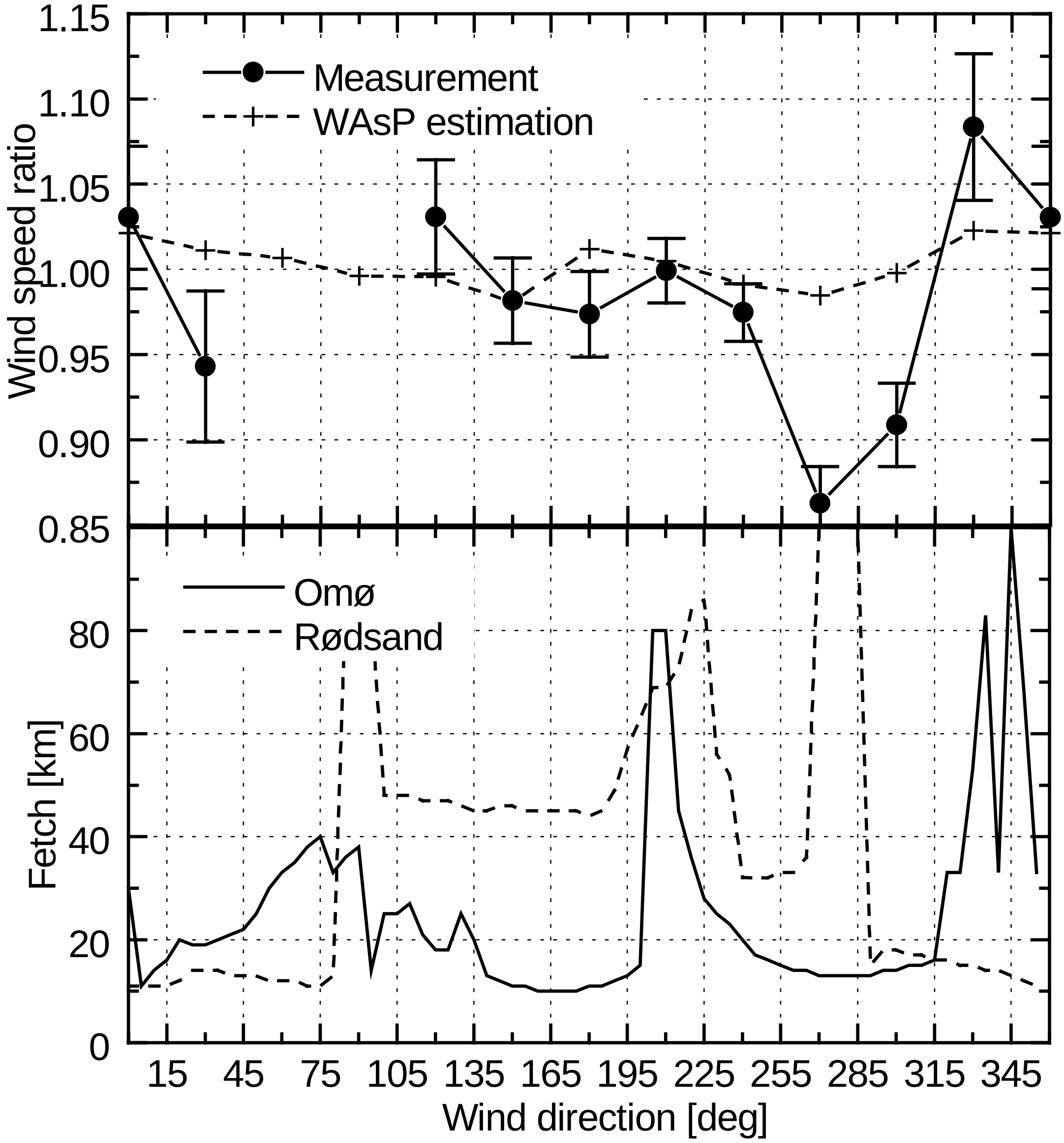


Figure 10: Omø / Rødsand: Measured and WAsP-predicted wind speed ratios (top) and sea fetches (bottom) versus wind direction

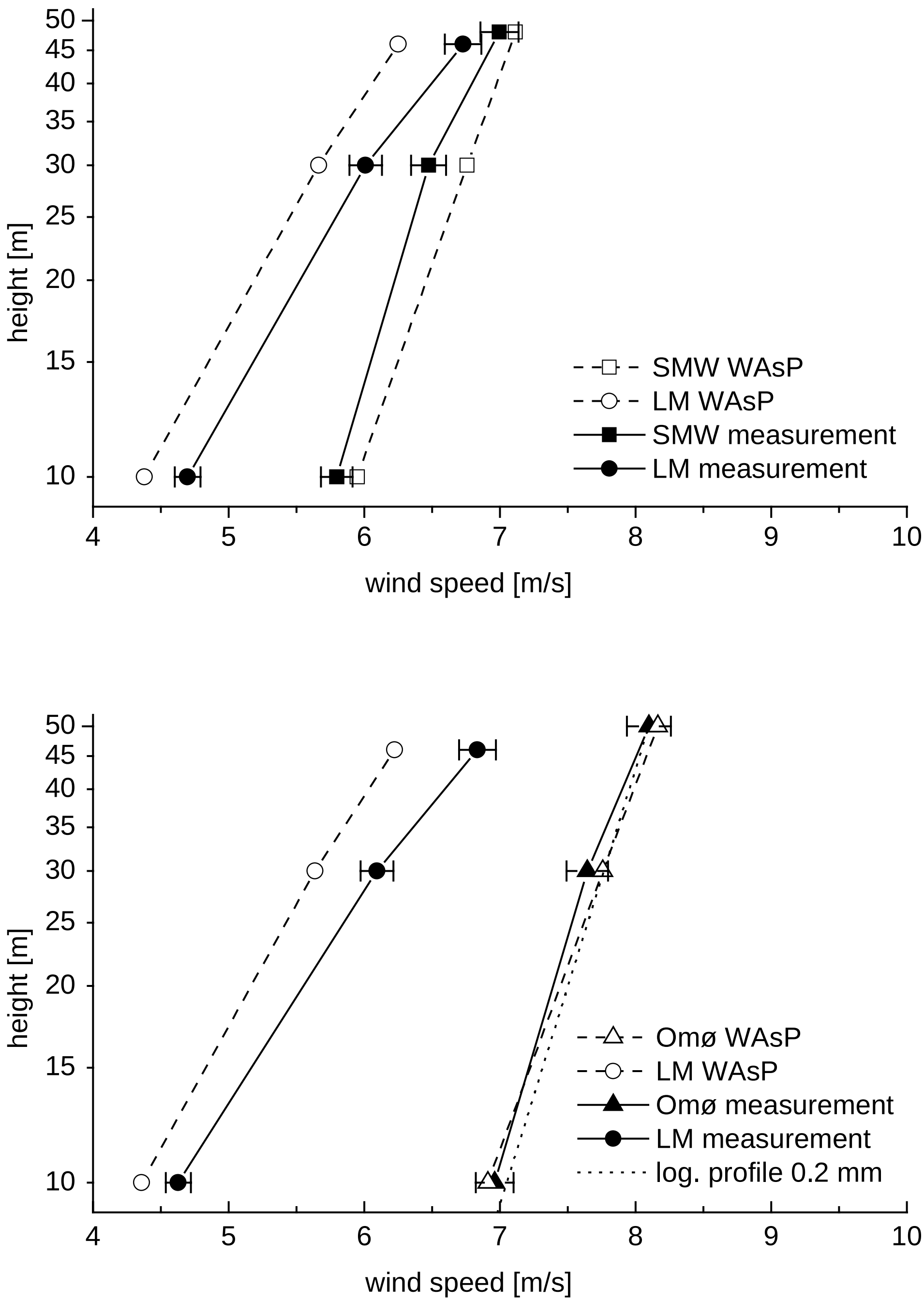


Figure 11: Measured and WAsP-predicted mean wind speeds for wind directions with land fetch situations (150° and 180° sectors) versus measurement heights (in logarithmic scale) for the two sites Vindeby LM and SMW (upper graph) and Vindeby LM and Omø (lower graph); the error bars show the 2% estimated uncertainty in the wind speed measurement

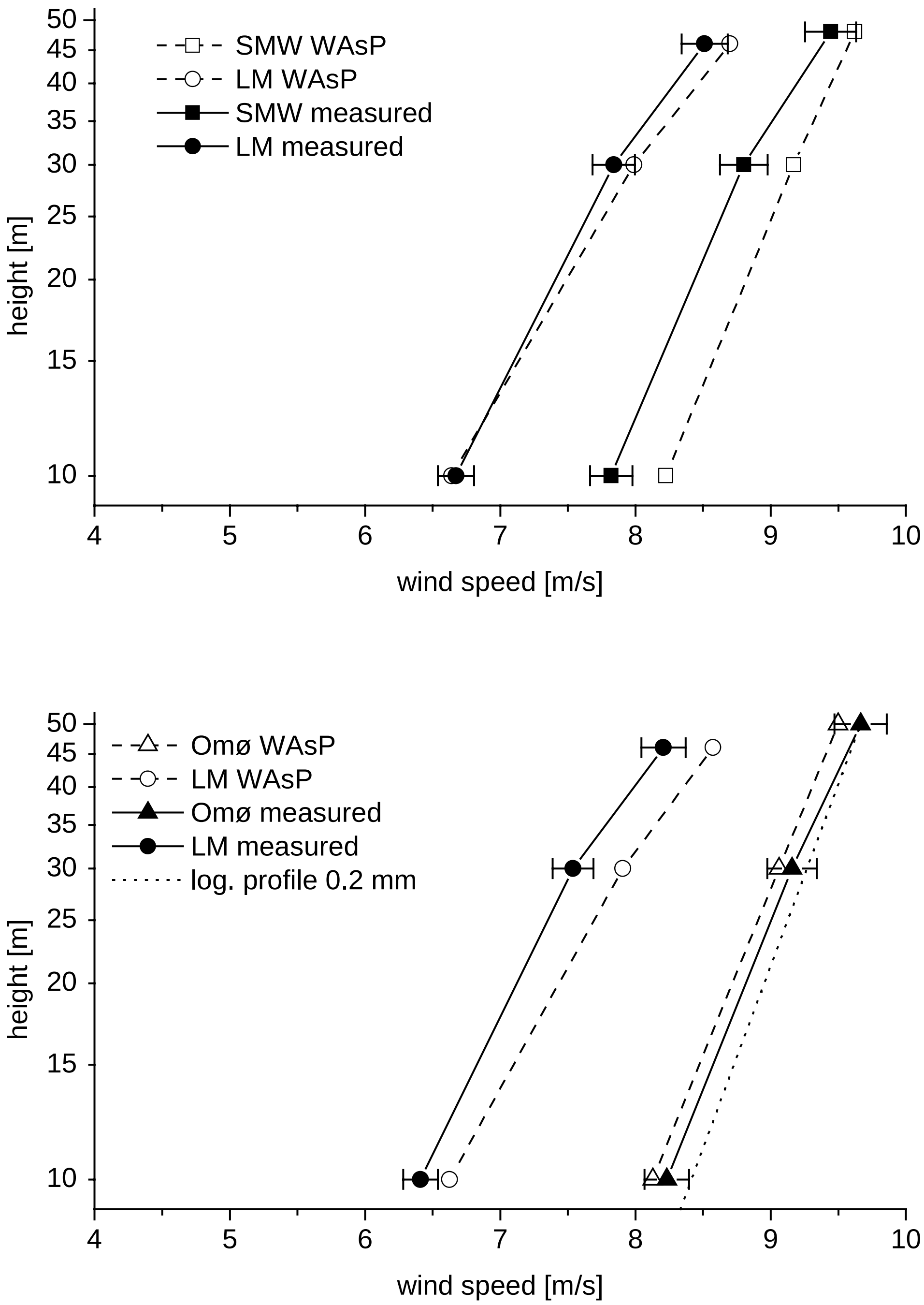
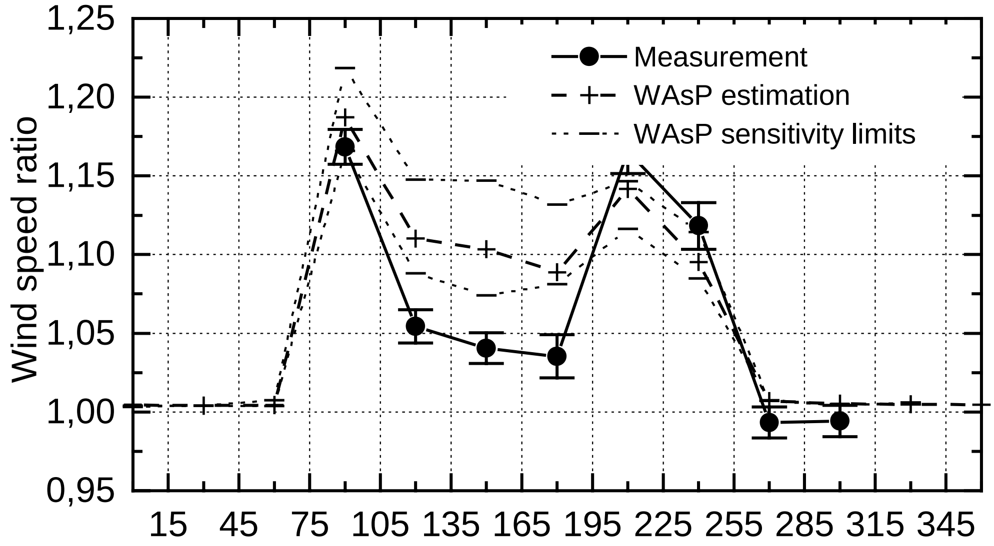


Figure 12: Measured and WAsP-predicted mean wind speeds for wind directions with different fetch situations (240° sector) versus measurement heights (in logarithmic scale) for the two sites Vindeby LM and SMW (upper graph) and Vindeby LM and Omø (lower graph); the error bars show the 2% estimated uncertainty in the wind speed measurement



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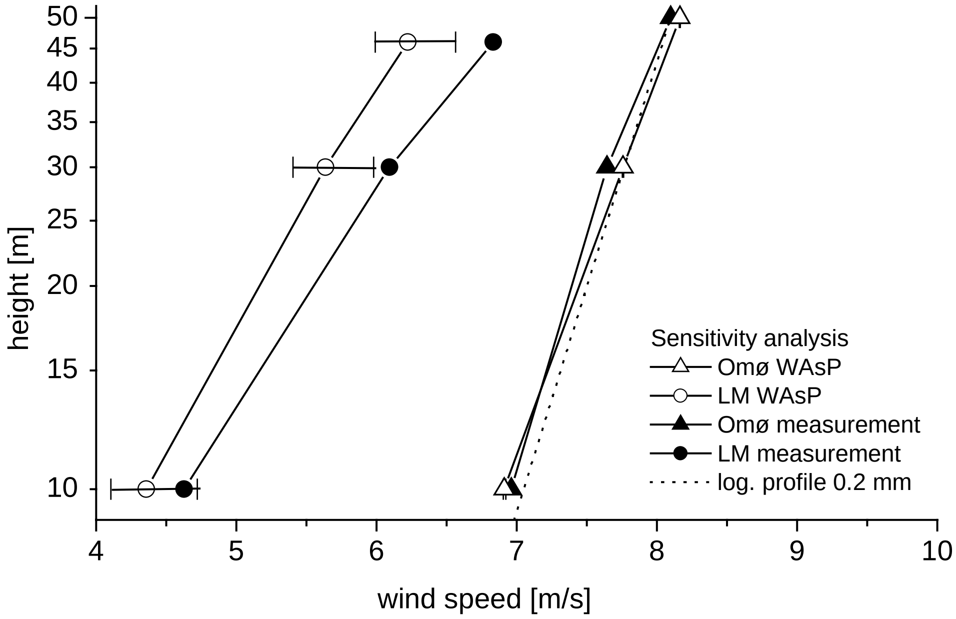

Figure 14: Sensitivity analysis: Measured and WAsP-predicted mean wind speeds for wind directions with land fetch situations (150° and 180° sectors) versus measurement heights (in logarithmic scale) for the two sites Vindeby LM and Omø; the error bars show the WAsP calculations with the two extreme high and low roughness estimates; measurement uncertainties are not shown here