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Research Article

Offshore Wind Resource Assessment with WAsP and MM5: Comparative Study for the German Bight

Barbara Jimenez, For Wind—Center for Wind Energy Research, University of Oldenburg, Oldenburg, Germany
Francesco Durante, DEWI—Deutsches Windenergie-Institut, Wilhelmshaven, Germany
Bernhard Lange*, R&D Division Information and Energy Economy, ISET—Institut für Solare Energieversorgungstechnik, Koenigstor 59, D-34119 Kassel, Germany
Torsten Kreutzer, Institute of Environmental Sciences, University of Vechta, Vechta, Germany
Jens Tambke, For Wind—Center for Wind Energy Research, University of Oldenburg, Oldenburg, Germany

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In this study, two different approaches to estimate the wind resource over the German Bight in the North Sea are compared: the mesoscale meteorological model MM5 and the wind resource assessment program WAsP. The dynamics of the atmosphere of the year 2004 was simulated with the MM5 model, with input from the NCEP global model, without directly utilizing measurement data. WAsP estimations were calculated on the basis of six measurement stations: three on islands, two offshore and one onshore. The annual mean wind speed at onshore, offshore and island sites is estimated by both models. The predictions are compared both with each other and with measured data. A spatial comparison of the wind resource calculated by the two models is made by means of a geographical information system. The results show that the accuracy of the WAsP predictions depends mainly on the measurement station used as input. Small differences are shown in the estimations performed by the three island stations, despite the large geographical distance between them. Compared with the measurements of the offshore sites, they seem to be suitable for estimating the offshore wind resource from measurements on land. The two offshore stations show differences when predicting each other's mean wind speed with the WAsP method, while the MM5 calculations show a similar deviation for both sites. The largest differences between the two models are found at distances of 5–50 km from the coast. While in WAsP the increase occurs in the first 10 km from the coast, MM5 models an increase due to coastal effects for at least 50 km.

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Introduction

There is increasing interest in using offshore sites for wind farms, particularly in Europe. However, to site an offshore wind farm optimally, it is necessary to have good estimates of the expected long-term average wind speed. In contrast to sites on land, offshore measurements are scarce and measurements at heights of prospec-

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* Correspondence to: B. Lange, R&D Division Information and Energy Economy, ISET—Institut für Solare Energieversorgungstechnik, Koenigstor 59, D-34119 Kassel, Germany.
E-mail: blange@iset.uni-kassel.de

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tive wind turbines are particularly rare. In coastal zones, where the first offshore wind farms are sited, prediction is complicated by changes in roughness and atmospheric stability at the coastline. Previous studies have shown that physical models can predict wind speed modifications reasonably well,[1] although differences in stability conditions on land and offshore are important.[2–5] Therefore the increasing interest in harvesting offshore wind energy requires reliable tools for wind resource estimation at these sites.

The most commonly used tool for wind resource predictions on land as well as offshore is the Wind Atlas Analysis and Application Program (WAsP).[6] WAsP is a computer program for predicting wind climates and power productions from wind turbines and wind farms. The predictions are based on wind data measured at stations in the same region. The program includes an analytic flow model, a roughness change model and a model for sheltering obstacles. In offshore areas, away from the influence of the coast, it gives good predictions in comparison with observed mean wind speeds and the wind speed profile.[7] A comparison with offshore masts in the Baltic Sea[8] showed a generally good performance, but also differences from the measurements for certain wind directions.

An alternative approach for wind resource assessment is the use of mesoscale meteorological models. A comparison between WAsP and the mesoscale model MIUU for the Baltic Sea showed important differences in some regions.[9]

The PSU/NCAR mesoscale model (known as MM5)[10] is a limited area, non-hydrostatic, terrain-following sigma-coordinate model designed to simulate or predict mesoscale atmospheric circulation. The model is supported by several pre- and postprocessing programs, which are referred to collectively as the MM5 modelling system.

The aim of this study is to investigate the capability of the two different approaches for wind resource assessment at offshore sites. Both models are used to assess the annual mean wind speed over the German North Sea region for the year 2004, where data from onshore (Wilhelmshaven), offshore (FINO platform and EMS lightship) and island (Norderney, Spiekeroog and Hallig Hooge) measurements are available. The two models are compared with each other and with the measured data. A geographical information system is used for a spatial intercomparison of the mean wind speed predicted by the two models. Owing to the availability of offshore wind measurements for comparison, the study is limited to a time period of 1 year. However, the methodology can be used unchanged for long-term wind resource assessments.

The structure of the article is as follows. In the next section the measurements are described. The models used in the study, WAsP and MM5, are briefly outlined in the following two sections. The fifth section contains the analysis of the results. Finally, conclusions are drawn in the last section.

Measurements

Observations from two offshore, one onshore and three island sites are used in this study. The locations of the measurement sites are shown in Figure 1. The stations are equipped with cup anemometers and wind vanes at different heights. Together with the coordinates of the stations, the measurement heights are given in Table I. Photographs of the measurement masts are shown in Figure 2.

The Wilhelmshaven (WHV) land mast is a high meteorological measurement mast located in northern Germany about 5 km from the coast. The mast is a dedicated wind measurement mast run by the company Projekt GmbH. It is situated in a wind turbine test site near Wilhelmshaven with presently 19 wind turbine prototypes of various European manufacturers. FINO (FN) and EMS are offshore sites located in the southwestern part of the North Sea. FINO is a 100 m high meteorological mast on an offshore research platform about 45 km to the north of the island of Borkum. The measurements are performed by the German Wind Energy Institute (DEWI) (www.fino-offshore.de). EMS is a lightship measurement site run by the German Weather Service (DWD). The Norderney (NR), Spiekeroog (SP) and Hallig Hooge (HH) measurement sites are situated on islands. NR and SP are located in the southern part of the North Sea about 8 km from the coast. HH is located in the eastern part of the North Sea about 5 km from the coast. All island sites are meteorological measurement sites of the DWD (www.dwd.de).

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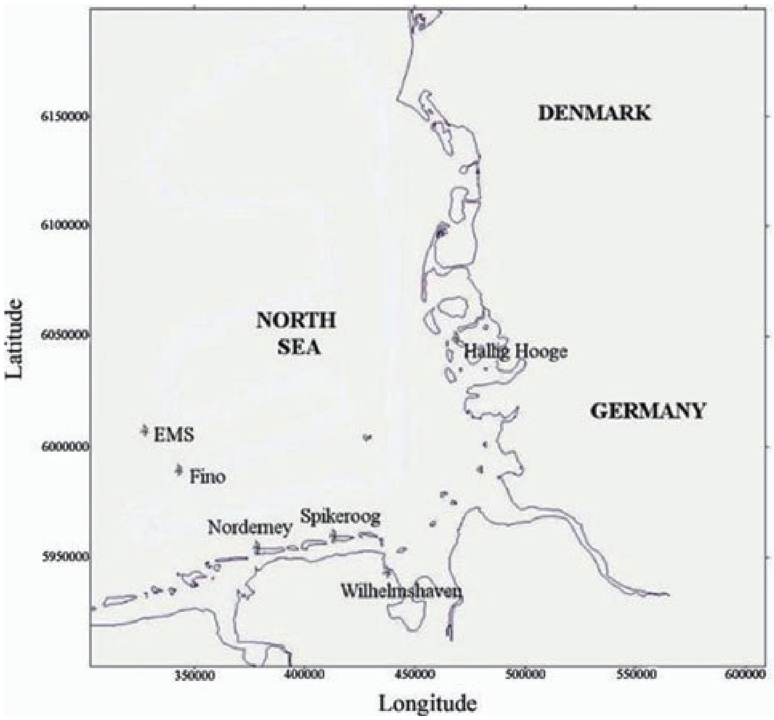

Figure 1. Locations of measurement sites

Table I. Locations and heights of the measurements (the anemometer heights used in this study are marked with an asterisk)

Site	Location (geographical coordinates)	Height (m)
FINO (FN)	54·01° N, 6·60° E	30, 40, 50, 60, 70, 80, 90, 100*
EMS	54·17° N, 6·35° E	10*
Hallig Hooge (HH)	54·58° N, 8·51° E	12*
Norderney (NR)	53·71° N, 7·15° E	12*
Spiekeroog (SP)	53·77° N, 7·67° E	10*
Wilhelmshaven (WHV)	53·60° N, 8·05° E	32, 62*, 92, 126, 130

Data from January to December 2004 have been collected at all measurement sites. Hourly mean data are used. All data have been quality controlled by visual inspection of the time series. Time periods where one of the measurements was erroneous or missing were taken out of consideration at all sites. In this way, time series with identical observation periods (time and date) have been obtained at all measurement stations. For 90% of the time, data from all stations were available simultaneously. The data completeness of the simultaneous time series for each month is shown in Table II.

The wind roses and wind speed histograms of the six measurement stations used are shown in Figure 3. The prevailing wind directions at offshore and land sites were from the sector northwest to southwest. The average wind speed at offshore sites was in the range 8·5–9·5 $\mathrm{m\,s^{-1}}$, while at the land site it was approximately 6·5 $\mathrm{m\,s^{-1}}$. Concerning the island sites, the prevailing wind direction in Norderney was from the southwest, while in Spiekeroog it was from the southwest, northwest and southeast. The average wind speed for both islands was 6–7 $\mathrm{m\,s^{-1}}$. Both islands are in the southern part of the North Sea. On the other hand, the prevailing wind direction at Hallig Hooge, in the eastern part of the North Sea, was from the sector southwest to north and the

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Figure 2. Photographs of measurement masts

Table II. Data completeness of the simultaneous time series of the measurement sites

Data completeness per month (%)											
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
95	91·6	48·4	99	96·7	97·9	97	74·3	84	95·4	95·1	95·4

average wind speed was almost 7·5 m s^{-1}. To determine the wind speed profile at FINO, the wind speed measurements of the FINO mast have been corrected for the effect of flow distortion caused by the measurement tower. The corrections have been made using a procedure based on the approach of Hoejstrup[11] and Lange *et al.*[12] A linear correction for the wind speed has been applied, i.e. the factors are independent of the magnitude of the wind speed. As a more natural form for the corrections than in the Hoejstrup model, we used

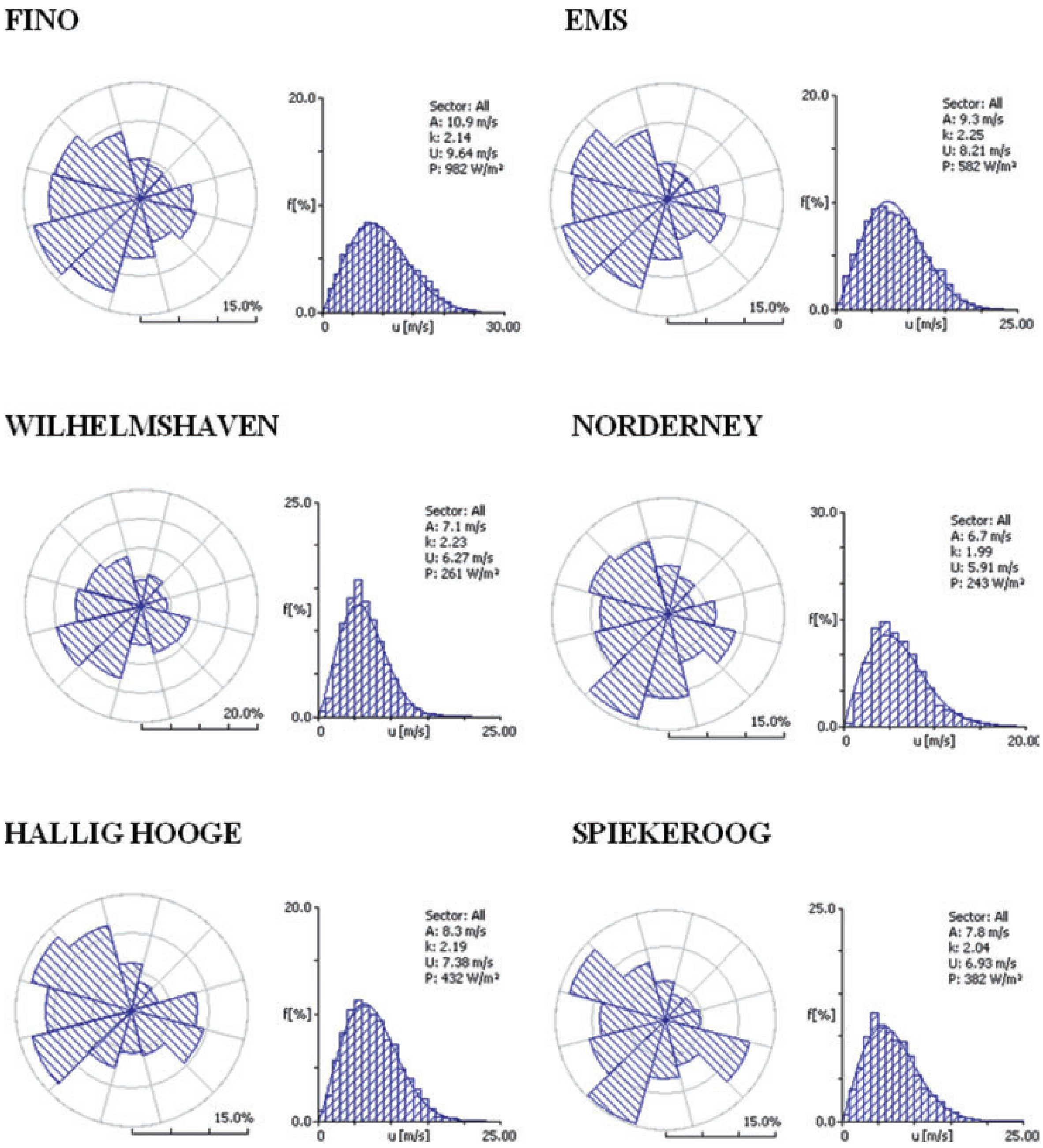

Figure 3. Wind roses and wind speed histograms (with fitted Weibull distributions)

correction factors that are a sinusoidal function of the wind direction. The function parameters were derived from comparisons between the wind speeds at different heights, especially between 103 and 91 m, and the anemometers on different sides of the mast. The top anemometer at 103 m height is not affected by the lattice mast, only by the lightning protection. The speed loss in front of the mast due to the dynamic pressure was 3·4% of the true wind speed, the overspeeding beside the mast reaches a maximum of 4·2%. The speed loss in the mast shadow is generally not sufficiently correctable: for the cup anemometers between 33 and 91 m,

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this situation occurs for wind directions from 280° to 360°. To determine the wind shear for these directions, data from ultrasonic anemometers positioned opposite the cup anemometers were used.

The Mesoscale Model MM5

Model Description

MM5 is a numerical weather prediction model developed by the Pennsylvania State University and National Center for Atmospheric Research with the ability to simulate atmospheric conditions with resolutions ranging from 100 to 1 km. Version 3 of MM5 is a non-hydrostatic, prognostic model with explicit description of pressure, momentum and temperature. The numerical solution is computed onto a rectangular-structured staggered grid by finite difference schemes. The vertical coordinate is terrain-following sigma. The physical package of MM5 consists of a set of parametrization schemes for cumulus, radiation, planetary boundary layer, microphysics and surface processes. A four-dimensional data assimilation scheme is implemented in the model with the capability of nudging the solution towards analysis or observations. A more complete description of the MM5 model can be found in Reference 10.

For wind speed predictions over land the spatial variability of the surface condition makes a high spatial resolution of the model necessary. This increases the computational effort greatly and prohibits long-term simulations for a larger area, as needed for wind resource maps. Offshore the surface conditions vary little in space, allowing a rather coarse spatial resolution of the model, which makes long-term calculations feasible.

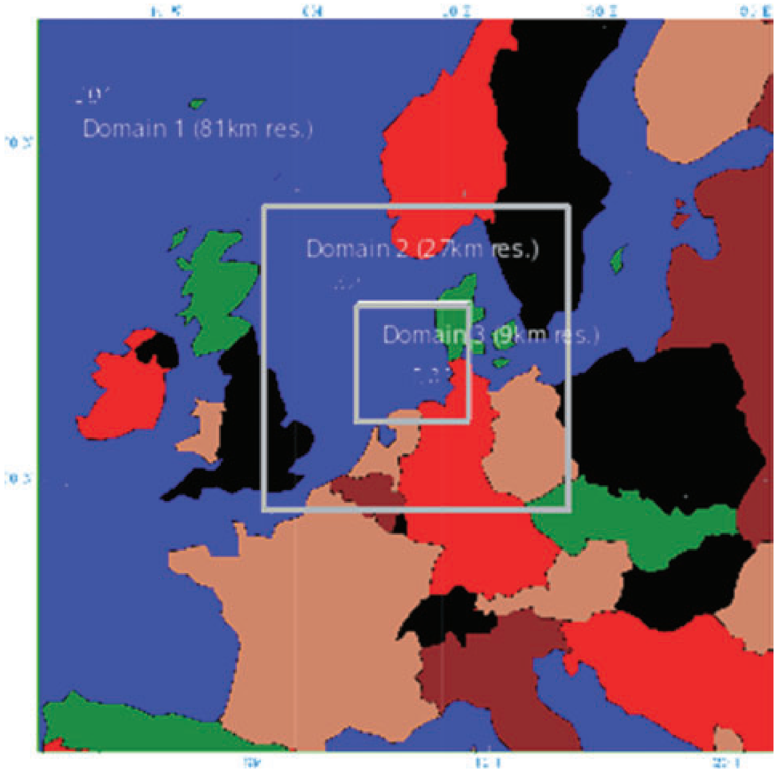

Figure 4. Simulation domains of the MM5 model

Application of the MM5 Model

In order to derive longer-term information about wind conditions occurring over the German Bight, the dynamics of the atmosphere of the year 2004 has been simulated with the MM5 model for the area shown in Figure 4. Three nested domains have been used, with horizontal resolutions of 81, 27 and 9 km respectively. According to the findings of Claveri *et al.*[13] and Durante *et al.*,[14] one-way nesting has been chosen between parent and child domains, the number of sigma levels in the vertical direction has been limited to 24 and the ETA Mellor–Yamada–Janijc PBL scheme was used to parametrize the boundary layer properties. Values of zonal and meridional components of the wind vector, relative humidity, air temperature, sea level pressure, geopotential height and surface temperature at a resolution of 2·5°, derived from the NCEP/NCAR reanalysis project database, provide initial and boundary conditions for the simulation.

One of the issues arising when performing hind-cast simulations for a period exceeding 1 week is the possibility for the solution to 'drift' away from the observed state of the atmosphere. In other words, the model can develop features that may differ significantly from the synoptic situation described by the boundary condition. To reduce this problem, nudging techniques together with the use of many consecutive shorter runs were applied.[15] Hence the simulation has been performed as 72 single runs each spanning a 5 day period. Also, the model's solution is nudged towards the analysis in the outer coarser domain at each time step.

Wind Atlas Analysis and Application Program (WAsP)

Model Description

WAsP is a widely used computer program that is able to generalize a set of surface wind observations into regionally representative wind climatology by modelling the wind flow across the landscape.

In the *analysis* mode the statistics derived from a set of long-term wind speed and direction data from a long-term reference site are extrapolated to the top of the boundary layer by fitting to a Weibull distribution and modelling the effects due to obstacles, terrain roughness and orography at the reference site. The resulting wind speed and direction statistics are known as *Wind Climate* and are representative of the geostrophic wind over the region. In the *application* mode a prediction of the wind resource at a candidate site is generated from the *Wind Climate* data by extrapolating down from the top of the boundary layer, effectively applying the reverse of the *analysis* process.

The WAsP model has been developed mainly for application over land, and its adaptation to offshore conditions is very limited. It is known that some physical effects exist offshore, which have an influence on the wind resources.

- The surface roughness of the sea depends on the wave field, while WAsP uses a constant roughness.
- Atmospheric stratification significantly influences the wind profile offshore also for higher wind speeds. WAsP uses a mean profile independent of the actual thermal stratification.
- The land–sea discontinuity gives rise to the development of an internal boundary layer (IBL), which is very dependent on the atmospheric stability. Also here WAsP uses a mean IBL.

Application of the WAsP Model

WAsP estimations were calculated using data from the six different measurement stations described above as input. Each station was visited to obtain an accurate description of any obstacles close to the site and a roughness description within a radius of approximately 10 km around the meteorological mast. Orographic effects have been neglected, since the area is very flat. A roughness map of the coastal area around the German Bight has been established (Figure 5). For each of the measurement stations a detailed roughness description (roughness rose) has been made on the basis of maps and a site visit.

Corrections due to obstacles were necessary at the Norderney and Spiekeroog sites (Table III). It can be seen that the corrections applied by WAsP are moderate at the Norderney site but quite important for some sectors at Spiekeroog.

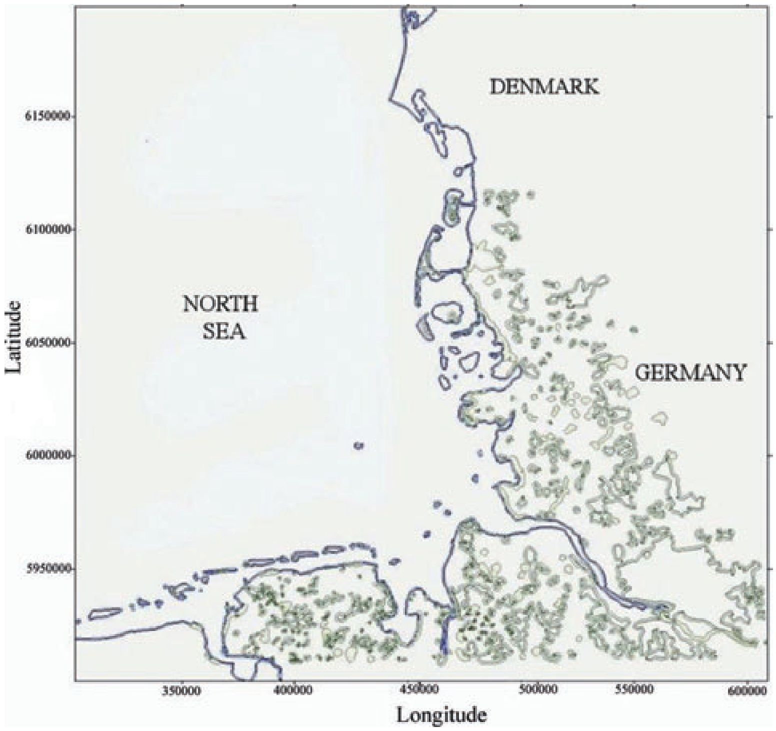

Figure 5. Roughness map of the coastal area around the German Bight

Table III. Corrections due to obstacles calculated by WAsP for Norderney (NR) and Spiekeroog (SP) for each of the 12 wind direction sectors

Sector	1	2	3	4	5	6	7	8	9	10	11	12
Angle (°)	**0**	**30**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**
NR (%)			−0·53	−0·53						−0·92	−8·46	−3·17
SP (%)		−0·63	−30·75	−35·41	−12·69	−10·19	−21·25	−2·43				

Table IV. Correction factors due to the shading effect of the wind farm in Wilhelmshaven (WHV) calculated by WAsP

Sector	1	2	3	4	5	6	7	8	9	10	11	12
Angle (°)	**0**	**30**	**60**	**90**	**120**	**150**	**180**	**210**	**240**	**270**	**300**	**330**
WHV (%)	−29·73	−14·09	−0·09	−7·35	−13·61	−12·49					−0·01	−11·02

Wind speed measurements at the Wilhelmshaven mast are disturbed for some wind direction sectors by the wakes of the wind turbines of the nearby wind farm. For a detailed description of the wind farm see http://www.dewi.de/. The measured wind speeds are therefore corrected for the shading effect of the turbines when they are bin averaged for 30° wind direction sectors. Correction factors for the site of the measurement mast have been established using the PARK model of WAsP (Table IV).

The default parameters of WAsP were used for the calculations. The average wind climatologies derived with WAsP from the six stations were applied to calculate the wind resource over the German Bight and the wind speed profiles at the measurement sites. The model has been applied to a digitized map with an area of about 190 km × 198 km for the region under investigation.

Results

The assessment of the MM5 and WAsP wind resource estimation methods will be performed by means of comparisons between:

- measured wind speed and WAsP predictions at the different sites;
- measured wind speed and predictions of both models at offshore sites;
- measured and predicted vertical wind speed profiles at FN;
- wind resource maps calculated by both models for the area of the German Bight.

WAsP Intercomparison

An intercomparison study has been performed with the WAsP model using each of the six measurements to predict the mean wind speed at the other five sites. Errors in the mean wind speeds were calculated between the WAsP predictions and measured data at the height of the measurements:

$$\text{error}\ (\%) = \frac{\overline{u}_{\text{predicted}} - \overline{u}_{\text{measured}}}{\overline{u}_{\text{measured}}} \times 100$$

Results of the comparison are shown in Table V.

From this it can be seen that WHV (on land) and the lightship EMS (offshore) differ greatly from all other sites. WHV is overpredicted by all other sites and itself severely underpredicts the other sites by 10%–15%, while for EMS it is the other way round, with a difference in the predictions of 7%–8%.

The two offshore sites FN (platform) and EMS (lightship) show relatively large differences when estimating each other and the other sites. In contrast, the three island stations NR, SP and HH show very similar predictions despite the large geographical distance between them.

This can also be seen when plotting the differences as a function of the distance from FN (Figure 6(a)) and NR (Figure 6(b)) to the other stations. It is found that the predictions from island and offshore stations, namely NR, SP, HH and FN, are in almost perfect agreement despite the large distances between some of them. On the other hand, WHV and EMS show very different results.

The WAsP predictions based on the FN site and island measurements agree rather well with each other, differing by only up to 2%.

Comparison between WAsP and MM5 at Offshore Sites

Measured and predicted mean wind speeds at the height of the offshore sites EMS (10 m) and FN (100 m) have been compared (Table VI). Identical observation periods (time and date) have been chosen for measurements and WAsP and MM5 outputs. The MM5 model shows an equal deviation for both sites: they are underestimated by approximately 4%. WAsP predictions differ depending on the reference station used. The three island

Table V. Percentage errors in the mean wind speed of the WAsP predictions compared with measurements

Predicted site			WAsP reference station					
Name	Measurement height (m)	Measured wind speed (m s^{-1})	NR (%)	HH (%)	SP (%)	WHV (%)	EMS (%)	FN (%)
Norderney	12	5·91	+0·6	+1·2	+0·3	−8·8	+7·2	−1·5
Hallig Hooge	12	7·38	+0·7	−0·4	+0·13	−10	+8	−0·1
Spiekeroog	10	6·93	−0·8	+0·7	−1·15	−9	+7	−1·7
Wilhelmshaven	62	6·27	+12·2	+12·2	+13·2	+0·4	+19·4	+11·6
Lightship EMS	10	8·21	−6·4	−6·4	−6·2	−16	−0·2	−6·9
FINO Platform	100	9·56	+1·6	+1·6	+1·9	−8·9	+7·9	+0·8

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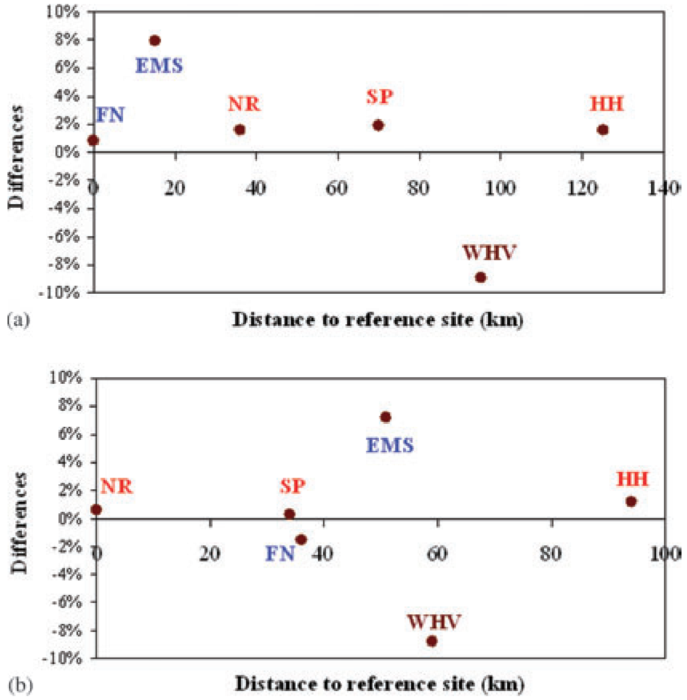

Figure 6. Differences in mean wind speed versus distance for (a) FINO and (b) Norderney sites

Table VI. Percentage errors in the mean wind speed between measured data and MM5 and WAsP predictions

Predicted site	WAsP reference station (%)							MM5
Name	Measurement height (m)	NR (%)	HH (%)	SP (%)	WHV (%)	EMS (%)	FN (%)	
Lightship EMS	10	−6·4	−6·4	−6·2	−16	−0·2	−6·9	−4·3
FINO Platform	100	+1·6	+1·6	+1·9	−9	+7·9	+0·8	−4·1

stations (NR, SP and HH) underestimate the wind speed at 10 m height at EMS by about 6% and slightly overestimate (2%) the wind speed at 100 m height at FN. However, the two stations FN and EMS exhibit a 7%–8% difference when predicting each other: EMS is underestimated by FN by 7% and FN is overestimated by EMS by 8%.

Vertical Wind Speed Profiles

Measured vertical wind speed profiles have been compared with those modelled by MM5 and WAsP at FN (Figure 7). Measurements are available at eight heights: 33, 41, 51, 61, 71, 81, 91 and 103 m. The wind speed measurements have been corrected for the effect of flow distortion caused by the measurement towers (see above). The WAsP profiles were calculated on the basis of the different measurements: NR, SP, HH, EMS and WHV.

All profiles modelled with WAsP show a similar shape, since only a mean profile is used by the model. The different predictions correspond to those found above. The WAsP profiles agree rather well with the FN

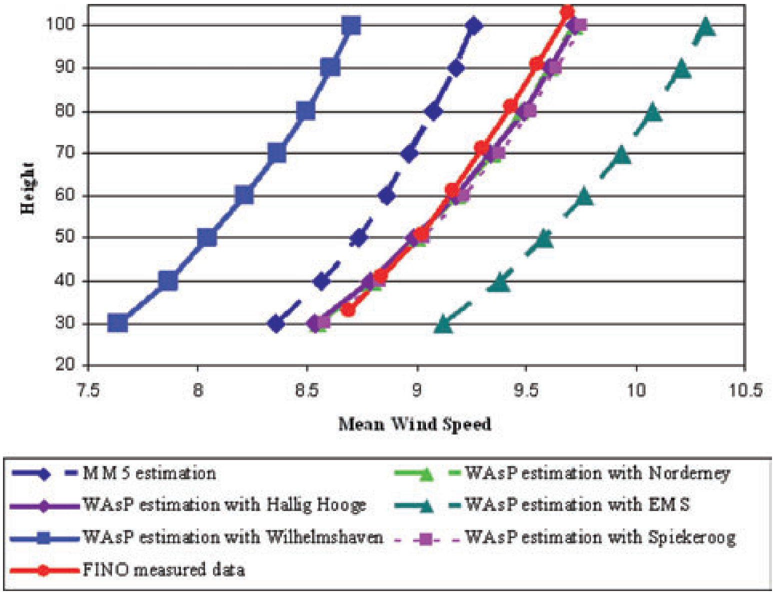

Figure 7. Vertical wind speed profiles at FINO from measured data and predicted by MM5 and WAsP on the basis of island (Norderney, Hallig Hooge), offshore (FINO, EMS) and onshore (Wilhelmshaven) measurements

measurements, mainly differing by a constant wind speed offset, whereas the MM5 profile shows a clear deviation.

Wind Resource Maps for the German Bight

Wind resource maps have been calculated for the area of the German Bight using both the WAsP method and the MM5 model with a grid resolution of 9 km (Figure 8). They were interpolated and visualized using a GIS tool. The interpolation method used was kriging. The WAsP maps were calculated on the basis of data from the FN, WHV and NR sites.

Large differences in the WAsP predictions for different reference stations as input can again be seen. It can also be seen that WAsP shows a large increase in the first 10 km when going offshore from the coastline, but no difference in mean wind speed over the sea further away from the coast. MM5, on the other hand, calculates a much slower increase in mean wind speed with increasing distance from the coast.

With the GIS tool the difference between the two models has also been visualized. It is shown in Figure 9 on the basis of FN as reference station for WAsP. It can be seen that the difference between the two models increases with decreasing distance to the coastline, and only very close to the coast does it seem to decrease again.

Conclusion

Two different methods to assess the wind speed profile at offshore sites have been evaluated and compared by means of example calculations of a wind speed map of the German Bight of the North Sea for the year 2004. The first is the widely used WAsP method, based on reference measurements; the second is the mesoscale model MM5. WAsP estimations were calculated on the basis of six different measurement stations: three islands, two offshore and one onshore. MM5 was run with data from the NCEP global model as input.

It was found that the results of the WAsP method largely depend on the measurement station used as reference. Four of the six stations investigated, namely the three island sites and the FN platform, predict each

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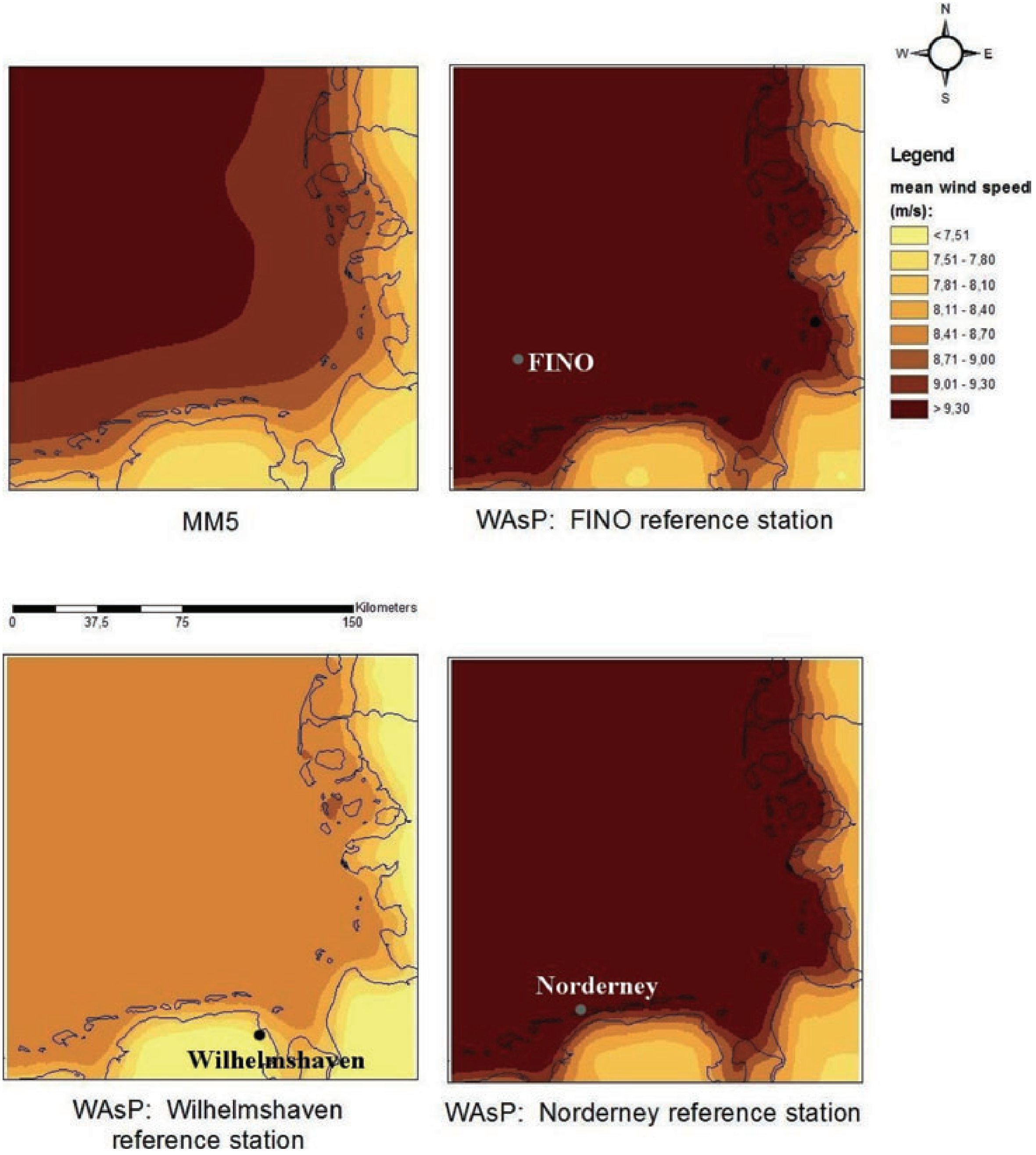

MM5

WAsP: FINO reference station

WAsP: Wilhelmshaven reference station

WAsP: Norderney reference station

Figure 8. Mean wind speed for 2004 predicted with MM5 and WAsP at 100 m height. Measurements at FINO, Wilhelmshaven and Norderney are used as reference in WAsP

other's mean wind speed with rather good accuracy (within ±2%) despite the large geographical distance between them. Compared with the predictions of the offshore sites, the island stations seem to be suitable for predicting the offshore wind resource from land-based meteorological measurements. On the other hand, two stations show rather high deviation: WHV, situated on land, and the lightship EMS. WHV underpredicts all other stations and is overpredicted by them, whereas for EMS it is the other way round.

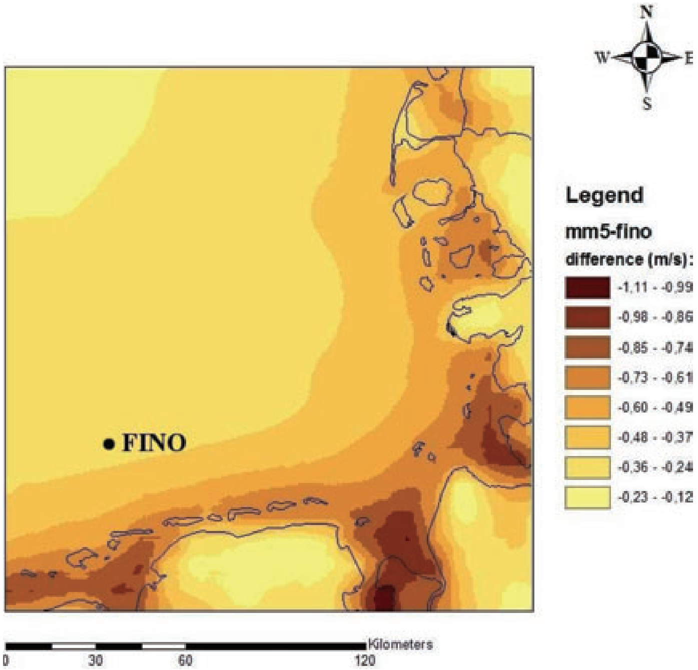

Figure 9. Difference in the annual wind resource at 100 m height predicted with MM5 and WAsP. FINO is used as reference station in WAsP

However, at both these stations the wind speed is measured in difficult conditions. At WHV the mast is located close to several wind turbines. Even though a correction has been applied to account for shading effects, there remains increased uncertainty in the measurements. EMS is a lightship measurement station, which might be subject to systematic errors due to flow distortion and ship movement. Wind speed measurements obtained from a ship-mounted anemometer are subject to bias caused by the presence of the ship distorting the airflow to the instrument.[16–18] The effect of the flow distortion on the ship's anemometer varies with the location, in some cases the flow could be accelerated by 5%–10%.[19]

The comparison of the vertical wind speed profile calculated by WAsP with that measured at FN shows rather good agreement. The increase in wind speed with height is only slightly underpredicted by WAsP. A more detailed analysis of the FN wind speed profiles can be found in Reference 20.

The results of the MM5 model show a deviation of about 4% from the measurements at both FN and EMS. The comparison of modelled and measured vertical wind speed profiles at FN shows that the prediction is good at low heights of 30 and 40 m, but the increase in wind speed with height is underpredicted, which leads to a difference of 4% at 100 m height. At EMS only a 10 m measurement is available. The measured wind speed there is underpredicted by MM5 in a similar way as it is by WAsP. As mentioned above, this might be due to a systematic measurement error. In conclusion, the WAsP predictions are rather good if the station with *input* data is suitable. Also, the mean wind speed profile used by WAsP seems to be suitable for the North Sea. Stations on islands south and east of the German Bight agree well with each other and the FN data. However, it is unknown if this also holds for offshore stations with different distances to the coast, since the largest differences between the two models were found at distances of 5–50 km from the coast. Therefore further validation is necessary.

The MM5 model shows promising results, with a deviation of about 4% offshore. Its main advantage is that no measurement data are needed. However, further development seems to be necessary, especially since the profile was shown to deviate from the mean wind speed FN profile.

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