Offshore wind resource assessment: Comparative study between MM5 and WAsP.

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Abstract: Electrical power from offshore wind farms can and should make an important contribution to the future energy demand and to climate protection. Accurate knowledge of the offshore wind resource is of crucial importance for the planning of wind farms. Contrary to sites on land, offshore measurements are scarce and knowledge about the coastal marine boundary layer is limited.
The most commonly used method for wind resource assessment is the European Wind Atlas method with the WAsP program. Despite its strong simplifications for offshore sites (constant sea surface roughness, a simple wind profile and a stability independent internal boundary layer model), it showed only small deviations in practical applications in comparison with wind measurements. An alternative approach for wind resource assessment is the use of mesoscale meteorological models.
In this study the wind resource over the German Bight in the North Sea is estimated using two different approaches: The mesoscale meteorological model MM5 with input from the NCEP global model without directly utilising measurement data, and the WAsP method with measurement data from offshore, coastal and land measurements.
The results are compared both with each other and with measured data from the FINO 1 offshore measurement platform, from a lightship, from three island masts and from a measurement station on land. A geographical information system is used for a spatial intercomparison of the model results.

1. Introduction

Accurate knowledge of the offshore wind resource is of crucial importance for estimating the wind resource in the planning of wind farms. Contrary to sites on land, offshore measurements are scarce and measurements at heights of prospective wind turbines are particularly rare. Therefore, 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 Wind Atlas Analysis and Application Program (WAsP) (Mortensen *et al.*, 1993). 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 (Petersen, 1992). A comparison with measurements from high meteorological mast close to the coastline supported this result (Petersen, 1993). A comparison with offshore masts in the Baltic Sea (Lange et al., 2001) showed a generally good performance, but also differences between model and 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 (Bergström and Barthelmie, 2002).
The aim of this study is to assess the offshore wind resource in the North Sea region using two models: The mesoscale meteorological model MM5 and WAsP. Data from the NCEP global model are used as input to MM5. Data from onshore (Wilhelmshaven), offshore (FINO platform and EMS lightship) and island (Norderney, Spiekeroog and Hallig Hooge) measurements are used as input in WAsP. Both models are compared with each other and with the measured data. A geographical information system is used for a spatial intercomparison of the wind resource predicted by both models.

The structure of the paper 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. Section 5 contains the analysis of the results. Finally, conclusions are drawn in the last section.

2. Measurements

The locations of the measurement sites used in this study 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 shown in table 1.

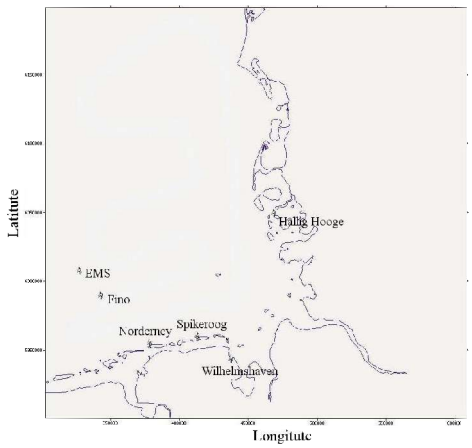


Figure 1: Locations of the measurement sites in and around the North Sea.

Table 1: Location and heights of the measurements (the anemometer heights used in this study are marked with *).

Site	Location (Geografical coordinates)	Height (m)
FINO	54.01° N; 6.6° E	30, 40, 50, 60, 70, 80, 90, 100*
EMS	54.17° N; 6.35° E	10*
Hallig Hooge	54.58° N, 8.51° E	12*
Norderney	53.71° N, 7.15° E	12*
Spiekeroog	53.77°N, 7.67°E	10*
WHV	53.6° N, 8.05° E	32, 62*, 92, 130, 162

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 nineteen wind turbine prototypes of various European manufacturers. The sites FINO (FN) and EMS are offshore sites located in the south-eastern 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 Borkum. The measurements are performed by the German Wind Energy Institute (DEWI). For more information on FINO, see www.fino-offshore.de. EMS is a lightship measurement 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 east of the North Sea about 5 km from the coast. All island sites are meteorological measurement sites of the DWD. For more information on the DWD sites, see www.dwd.de. Photographs of the measurement stations are shown in figure 2.
Data from January to December 2004 have been used in this study. Hourly data are used. All data have been quality controlled by visual inspection of the time series. Time periods where one measurement was erroneous or missing were taken out of consideration at all sites. In this way the same records (date and time) have been chosen at all the measurement stations. The data completeness of the simultaneous time series is shown in table 2.

The wind roses and wind speed histograms of the six measurement stations used are shown in figure 3.

Table 2: Data completeness used in the different measurement sites.

Data completeness per month (%)												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
2004	95	91,6	48,4	99	96,7	97,9	97	74,3	84	95,4	95,1	95,4

Figure 2: Photographs of measurement masts: Wilhelmshaven (WHV), Norderney (NR), Spiekeroog (SP), Hallig Hooge (HH), FINO (FN) and lightship Ems (EMS).

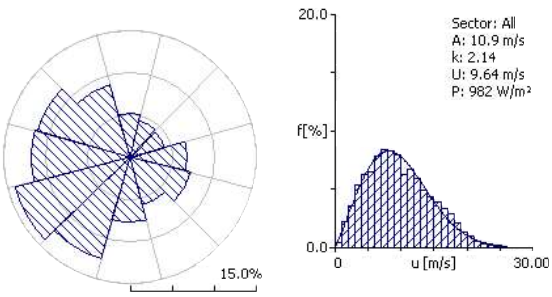
3. The MM5 model

MM5 is a numerical weather prediction model developed by the Pennsylvania State University and National Center for Atmospheric Research with the ability to simulate the atmospheric conditions with resolution ranging from 100 km 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 the rectangular structured staggered grid by finite difference schemes. The vertical coordinate is terrain-following sigma. The physical package of MM5 is made up by a set of parameterization 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 Grell *et al.* (1994).

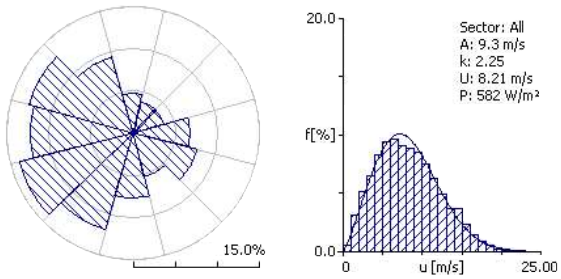
In order to derive longer term information about wind conditions occurring over the German Bight, the dynamics of the atmosphere of the year 2004 has been simulated with the MM5 model for the area shown in figure 4. Three nested domains have been used, with horizontal resolutions of 81, 27 and 9 km, respectively. According to findings of Claveri et al. (2005) and Durante et al. (2005) one-way nesting has been chosen between parent and child domains, the number of sigma level in the vertical direction has been limited to 24 and the ETA Mellor-Yamada-Janijc PBL scheme was used to parameterize the PBL properties. Values of zonal and meridial components of the wind vector, relative humidity, air temperature, sea level pressure, geopotential height and surface temperature, at

a resolution of 2.5 degrees 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 one 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. Hence, the simulation has been performed as 72 single runs each spanning a five day period. Also, the solution is continuously nudged towards the analysis in the outer coarser domain.
The same records (date and time) between measurement stations and MM5 have been chosen, in order to compare the MM5 and WAsP results.

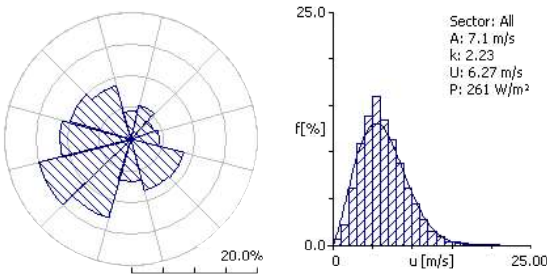
FINO



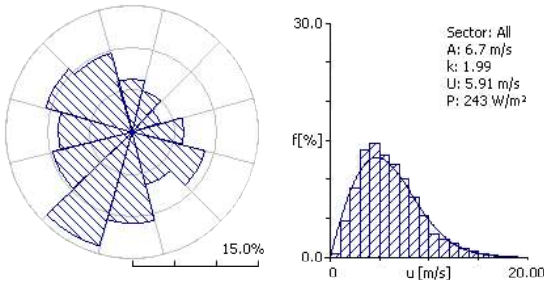
EMS



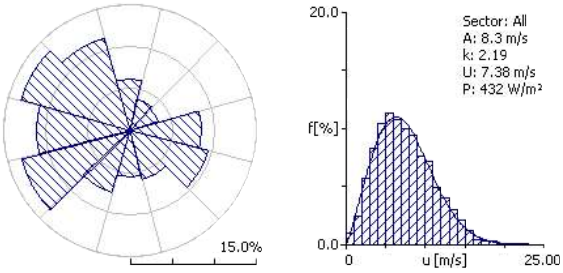
WILHELMSHAVEN



NORDERNEY



HALLIG HOOGE



SPIEKEROOG

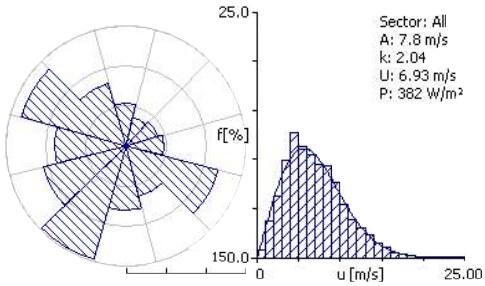


Figure 3: Wind roses and wind speed histograms (with fitted Weibull distributions) for: FINO, EMS, Wilhelmshaven, Norderney, Spiekeroog and Hallig Hooge.

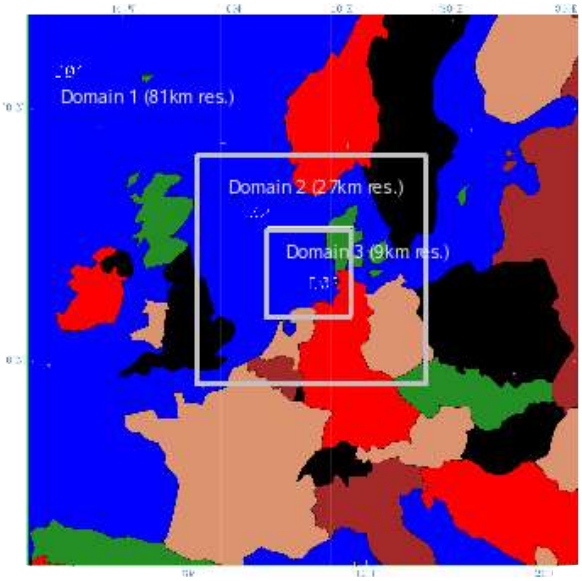


Figure 4: Simulation domains of the MM5 model

4. Application of the WAsP model

WAsP estimations were calculated using the six different measurement stations described in section 2 as input. The default parameters of WAsP were used for the calculations. The 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. For this, a roughness map of the coastal area around the German Bight has been established (see figure 5). Orographic effects have been neglected, since the area is very flat. For each of the measurement stations, a detailed roughness description has been made on the basis of maps and a site visit.

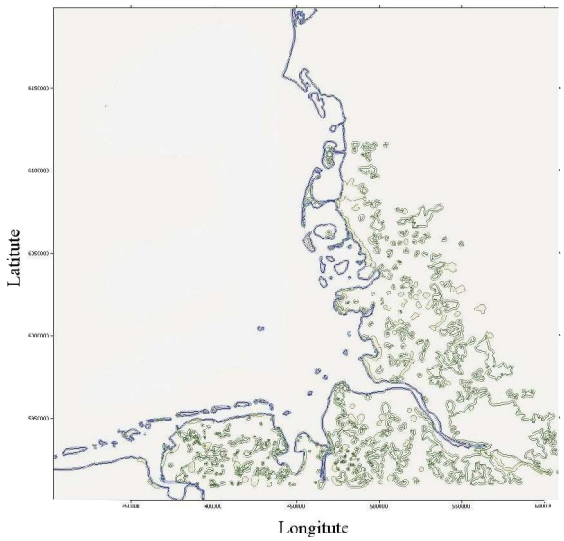


Figure 5: The roughness map of the coastal area around the German Bight.

Corrections for obstacles were necessary for the Norderney and Spiekeroog sites. The applied correction for the different sectors is shown in table 3.

Table 3: Obstacle correction in Norderney and Spiekeroog.

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**
Norderney			-0.53	-0.53						-0.92	-8.46	-3.17
Spiekeroog		-0.63	-30.75	-35.41	-12.69	-10.19	-21.25	-2.43				

Wind speed measurements at the Wilhelmshaven mast is disturbed for some wind direction sectors by 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. Corrections factors for the site of the measurement mast have been established using the PARK model of WAsP (table 4).

Table 4: Corrections due to the shading effect of the wind farm in Wilhelmshaven.

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**
Wilhelmshaven	-29.73	-14.09	-0.09	-7.35	-13.61	-12.49					-0.01	-11.02

5. Results.

The assessment of the MM5 and WAsP wind resource estimations will be made by means of the comparison between;

- Measured wind speed and WAsP predictions in the different sites.
- Measured wind speed and both models predictions at offshore sites.
- Wind resource maps calculated by both models with a geographical information system for the area of the German Bight.

5.1 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. The result is shown in table 5. The differences in mean wind speed in percent were calculated between the measured data and WAsP predictions at the height of the measurements.

Table 5: Difference in mean wind speed between measurements and WAsP predictions in percent.

Predicted site				**WAsP-Reference station**					
Name	**Abb.**	**Meas. Height**	**Meas. wind speed**	NR	HH	SP	WHV	EMS	FN
Norderney	NR	12 m	5.91	+0.6%	+1.2%	+0.3%	-8.8%	+7.2%	-1.5%
Hallig Hooge	HH	12 m	7.38	+0.7%	-0.4%	+0.13	-10%	+8%	-0.1%
Spiekeroog	SP	10 m	6.93	-0.8%	+0.7%	-1.15	-9%	+7%	-1.7%
Wilhelmshaven	WHV	62 m	6.27	+12.2%	+12.2%	+13.2%	+0.4%	+19.4%	+11.6%
Lightship Ems	EMS	10 m	8.21	-6.4%	-6.4%	-6.2%	-16%	-0.2%	-6.9%
FINO Platform	FN	100 m	9.56	+1.6%	+1.6%	+1.9%	-8.9%	+7.9%	+0.8%

From the results it is clear that the Wilhelmshaven site differs very much from all other sites. It is overpredicted by all other sites by up to 20% and itself severely underpredicts the other sites.
It can be seen that for the three island stations, the difference in their estimations is small, despite their large geographical distance between Norderney, Spiekeroog and Hallig Hooge. At the offshore sites, they underpredict the lightship Ems and only slightly overpredict the FINO platform measurement.

The two offshore sites Fino and lightship Ems show relatively large differences (7-8%) when estimating each other. However, it has to be kept in mind that there is a large height difference in these measurements. It can be seen that the offshore stations are predicted as well by the island stations as by each other.
Therefore, if offshore and island stations are used as reference in WAsP model, the predictions agree rather well with the measurements at offshore and island sites.

5.2 Comparison between WAsP and MM5 for the measurement sites

For the offshore measurement sites, Lightship Ems and FINO Platform, the results of WAsP and MM5 can be compared. Table 7 shows the difference in mean wind speed in percent between the measured data, WAsP and MM5 predictions at the height of the measurements. Differences are in the range of +/- 6%. For MM5, an underprediction of 4% is found for Ems (10m) and FINO (100m). With WAsP, the two stations FINO and Ems exhibit a 7-8% difference, e.g. Ems is underestimated by Fino by 7% and Fino is overestimated by Ems by 8%. The three island stations Norderney, Spiekeroog and Hallig Hooge show very similar predictions of the offshore sites. They all underestimate the wind speed at 10m height at lightship Ems, and slightly overestimate the wind speed at 100 m height at FINO.
Clearly, the difference between the two offshore measurements, lightship Ems and FINO, is not captured by WAsP independent of the reference station used. In contrary, the MM5 model shows an equal deviation for both sites. Both sites are slightly underestimated.

Table 7: Difference in mean wind speed between the measured data, MM5 and WAsP predictions in percent.

Predicted site	**WAsP-Reference station**								**MM5**
Name	**Abb.**	**Meas. height**	NR	HH	SP	WHV	EMS	FN	
Lightship Ems	EMS	10 m	-6.4%	-6.4%	-6.2%	-16%	-0.2%	-6.9%	-4.3%
FINO Platform	FN	100 m	+1.6 %	+1.6 %	+1.9 %	-8.9%	+7.9 %	+0.8 %	-4.1%

5.3. Wind potential over the German Bight

Wind resource maps have been calculated for the area of the German Bight with both the WAsP method and the MM5 model with a grid resolution of 9 km. They were interpolated and visualised using a GIS tool. The interpolation method used was kriging. The maps are shown in figure 7. For WAsP, the calculations with FINO, Wilhelmshaven and Norderney as reference stations are shown here.
Large differences of the WAsP predictions for different reference stations as input can be seen again. It can also be seen that WAsP shows a large increase in the first 10 km when going offshore and 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 to the coast.
With the GIS tool, also the difference between the two models has been visualised. It is shown in figure 8 for the example of FINO as reference station for WAsP. It can be seen that the difference between both models increases with decreasing distance to the coastline, and only very close to the coast it seems to decrease again.

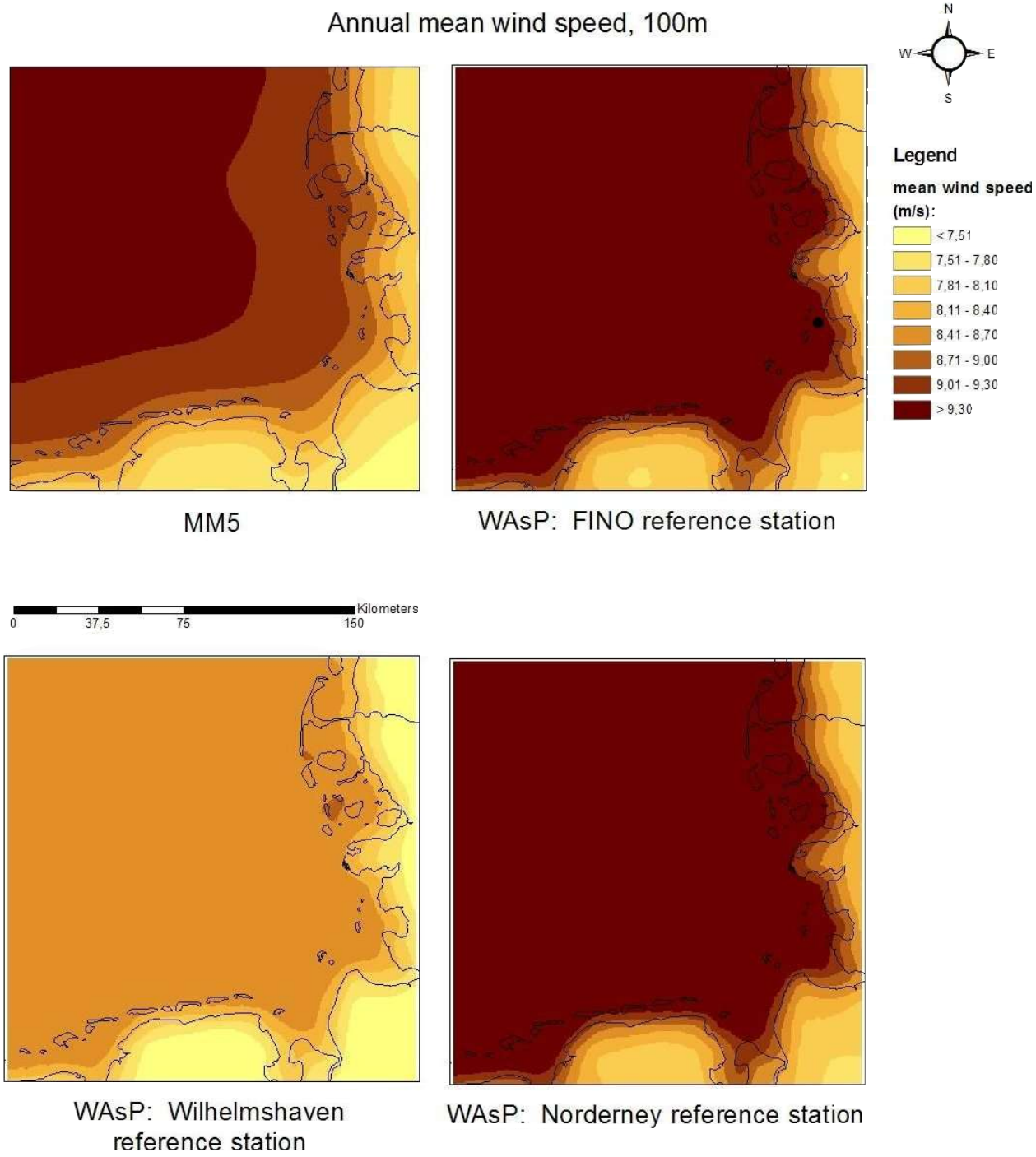


Figure 7: Mean wind speed for 2004 predicted with MM5 and WAsP at 100 m height. Measurements at FINO, Wilhelmshaven, and Norderney are used as reference in WAsP.

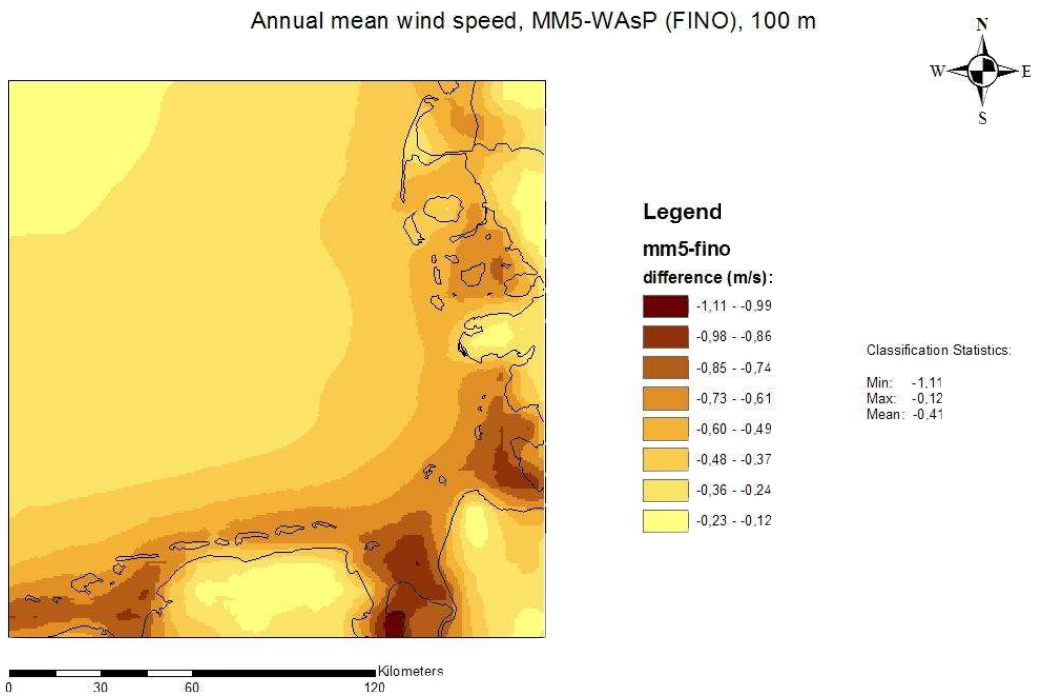


Figure 8: Difference in the annual wind resource predicted with MM5 and WAsP model at 100 m height. FINO, is used as reference station in WAsP.

6. Conclusion

WAsP and MM5 are used to assess the offshore wind resource in the North Sea region. Six different stations are used as reference in the WAsP model: three islands, two offshore and one onshore. Predictions at onshore, offshore and islands sites are made by both models. It has been performed:

- An intercomparison with the WAsP model using each of the six measurements to predict the mean wind speed at the other five sites.
- A comparison between the measured data and both model predictions at offshore sites far away of the influence of the coast.
- Comparison of the wind resource maps calculated for the area of the German Bight by both models.

In terms of average wind speed, the differences between the predictions performed by the WAsP models at different sites depend on the measurement station used as reference.

The two offshore stations used, the lightship Ems at 10 m height and the FINO platform at 100 m height, show differences when predicting each other with the WAsP method. On the other hand, the MM5 calculations show the same deviation for both sites. The reason for this behaviour has to be investigated further. Different explanations are possible: lightship Ems is further offshore and might have higher wind conditions, the height difference is modelled differently by WAsP and MM5 or the measurements of the lightship might be subject to systematic errors due to flow distortion and ship movement.

For the three island stations, the difference in their estimations is small, despite their large geographical distance between some of them. Compared to the predictions of the offshore sites, they seem to be suitable for predicting the offshore wind resource from measurements on land.

The onshore station Wilhelmshaven clearly shows very different wind conditions. It is not clear, however, if this is due to the onshore location or due to the difficult measurement situation close to the wind farm.

The difficulty of using WAsP is to find a suitable measurement station. From the stations used in this study, the onshore station Wilhelmshaven is clearly not usable. For the other stations, it could be seen that deviations between different measurement stations used as input are at least in the same range as differences between the WAsP and MM5 models.
The MM5 model does not use any measurement data as input. Taking this into account, the deviations found from the offshore measurements are with about 4% rather small. Although further validation is necessary, this is an encouraging result for the use of MM5 for offshore wind resource prediction.
When comparing the spatial behaviour of the resource estimations for the German Bight from both models, it can also be seen that the increase of wind speed with distance to the coast is much quicker in the WAsP model than in MM5. While in WAsP the increase occurs in the first 10 km from the coast, MM5 model an increase due to coastal effects for at least 50 km. As a result, the largest differences between the two models can be seen at distances from the coast of 5 to 50 km.
Using different models and measurement data led to differences of up to 8% in estimated mean wind speed for the offshore sites. This is clearly too much for a reliable planning of offshore wind farms. Further validation and development of the models is needed. At present, still on-site measurements seem necessary to reliably predict the mean wind speed at offshore sites.

Acknowledgement
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Referees

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