Evaluation of Offshore Wind Simulations with MM5 in the Japanese and Danish Coastal Waters

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Summary

In order to evaluate the accuracy of offshore wind simulation with the mesoscale model MM5, long-term simulations are performed for Ise Bay, located in central Japan, and for Horns Rev, located off the west coast of Denmark, and the accuracy of the simulations is evaluated using in situ measurements at both sites. In the Ise Bay case, the simulation is done for one year, and the evaluation using measurements at a marine tower with an anemometer at 18 m shows that the biases of monthly mean wind speeds are -1.46 to 0.00 m/s (-30.7 to 0.0 % of the mean wind speed), the root-mean-square errors (RMSEs) are 2.14 to 3.11 m/s (32.7 to 54.3 %) and correlation coefficients are 0.52 to 0.82. In the Horns Rev case the simulation is performed for one month, and the biases, RMSEs and correlation coefficients for four anemometers on a meteorological mast (10 m, 30 m, 45 m, and 62 m heights) are -0.25 to 0.41 m/s (-2.2 to +4.5 % of the mean wind speed), 1.37 to 1.46 m/s (12.5 to 16.2 %) and 0.92 to 0.95, respectively. The accuracy for Ise Bay is found to be more than twice as bad as that for Horns Rev, in terms of the relative RMSE. This suggests a difficulty to simulate offshore wind conditions in the Japanese coastal waters even using a mesoscale model, compared to the Danish ones. This is mainly due to the complexity of the wind climate strongly influenced by dynamical effects from complex terrains and thermodynamical effects such as land-sea breezes.

1. Introduction

Recently, needs for offshore wind resource assessment have been rapidly growing all over the world, with the increase of interests in renewable energy and of knowledge that offshore winds can be a promising energy source. However, it is generally difficult to know wind climate over coastal waters, where offshore wind farms are usually constructed, because wind observation is usually few as well as the winds in coastal waters vary complicatedly in both time and space compared to those in open oceans.

Up to the present, the authors have investigated the accuracy of the wind simulation with a mesoscale meteorological model for areas in Japan (e.g., [1], [2]), especially for Ise Bay. Ise Bay is a shallow bay with an area of 2,342 km^2 and located in the central part of Japan, heading its mouth for the Pacific. Our previous study ([3]) shows that Ise Bay is rare shallow coastal waters with relatively sufficient wind energy potential in the central part of Japan. Therefore, it is necessary to evaluate the simulation accuracy with the mesoscale model in depth, in order to assess the offshore wind resource more accurately.

On the other hand, Horns Rev, located off the west coast of Denmark, is well-known as the first largest offshore wind farm in the world. Before the wind farm construction, an in-depth wind observation had been done at a meteorological mast with the height of 62 m. The data is thought to be very precious as a measure of pure ocean winds. Thus, in this study, the Horns Rev met. mast data is used for understanding the accuracy of the mesoscale mode simulation for the pure ocean winds as well as winds at a hub height. The accuracy is then compared with that of the simulation for Ise Bay, in which the winds are expected to be greatly affected by more complex terrains and stronger solar radiation, compared to the Danish coastal waters.

2. Method of simulation and evaluation

The model used in this study is the fifth-generation mesoscale model MM5 version 3.7, developed by Pennsylvania State University and National Center for Atmospheric Research (NCAR). General descriptions of this model are given by [4] and [5]. MM5 is a fully compressible, non-hydrostatic model with a large number of physics options regarding cloud microphysics, radiation, planetary boundary layer (PBL) and surface processes. The model also includes multiple nesting and four-dimensional data assimilation options, which enable us to hindcast meteorological conditions realistically.

Model configurations and input data used for the simulations in this study are listed in **Table 1**. And, domains of the

Table 1 Model configurations used in the simulations

	Ise Bay	Horns Rev
Period	April 2001 through March 2002 (1 year)	January 2002 (1 month)
Input data	6-houlry 10km x10km JMA Meso Analysis Weekly NOAA-Reynolds SST	6-houlry 1deg x 1deg NCEP FNL Analysis Weekly NOAA-Reynolds SST
Nesting	2-way nesting	2-way nesting
Domain	Domain 1: 3 km (161x158 grids) Domain 2: 1 km (118x118 grids)	Domain 1: 18 km (100x100 grids) Domain 2: 6 km (100x100 grids) Domain 3: 2 km (100x100 grids)
Vertical layer	20 levels (Surface to 100 hPa)	26 levels (Surface to 100 hPa)
Time step	Domain 1: 9 sec Domain 2: 3 sec	Domain 1: 54 sec Domain 2: 18 sec Domain 3: 6 sec
Physics options	Simple Ice microphysics scheme No cumulus parameterization scheme Shallow convection scheme Cloud-radiation scheme Eta PBL scheme Five-layer soil model	Mixed-Phase microphysics scheme Grell cumulus parameterization scheme Shallow convection scheme Cloud-radiation scheme Eta PBL scheme Five-layer soil model
4DDA	On	On, except for PBL of Domain3

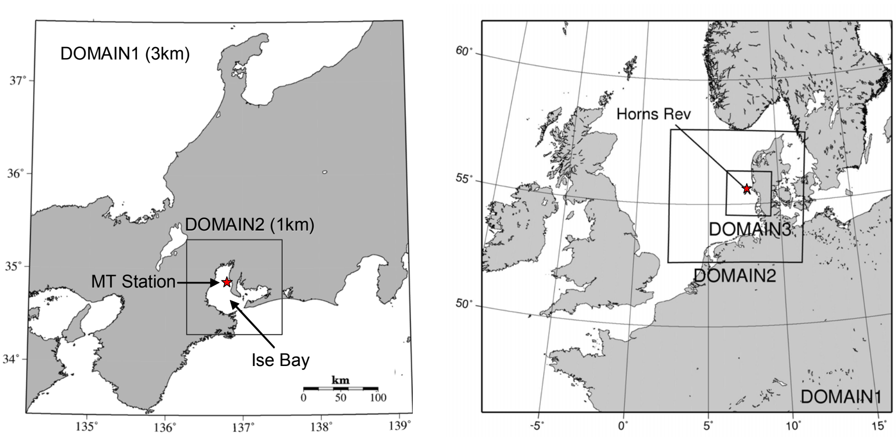

Fig. 1 Location of (a) Ise Bay and (b) Horns Rev and domains used in each simulation.

simulations and location of the target observation stations are shown in **Fig. 1**. MM5 is run with the 2-way nesting option for two or three domains gradually focusing on each target observation station. The simulation is performed for one year in the Ise Bay case, and one month in the Horns Rev case. The objective analysis input into MM5 is the 6 hourly Japan Meteorological Agency Mesoscale Analysis (MANAL) with a 10km×10km grid spacing for the Ise Bay case, and the 1°×1° NCEP (National Center for Environmental Prediction) FNL Analysis for the Horns Rev case. These objective analysis data are used for 4-dimentional data assimilation as well as for initial and boundary conditions.

In **Table 1**, physics options used in the simulation are also shown. Regarding the PBL scheme, the Eta scheme [6] is used in both cases. The Eta scheme is the PBL scheme utilized in the NCEP operational regional model Eta. The scheme is based on the Mellor-Yamada (M-Y) turbulence closure model predicting turbulent kinetic energy (TKE), and is generally called 1.5-order closure scheme. Unlike other PBL schemes implemented in MM5, in the Eta scheme the non-local vertical mixing in the unstable condition is not taken into account.

The accuracy of the simulation is evaluated using in-situ measurement data. In the case of Ise Bay, data from a marine tower, referred to as MT Station hereafter, is used. The MT Station is located roughly 4 km off the coastline of the Chita Peninsula (**Fig. 1a**), and wind speed and direction are measured at the height of 18 m on the tower (**Fig. 2a**). The data of one year from 1 April 2001 to 31 March 2002 are used to evaluate the accuracy of the simulation for Ise Bay. In the case of Horns Rev, data from a meteorological mast is used. The meteorological mast is located in the North Sea approximately 20 km off the west coast of Denmark (**Fig. 1b**). On the mast, cup anemometers are set at 15,

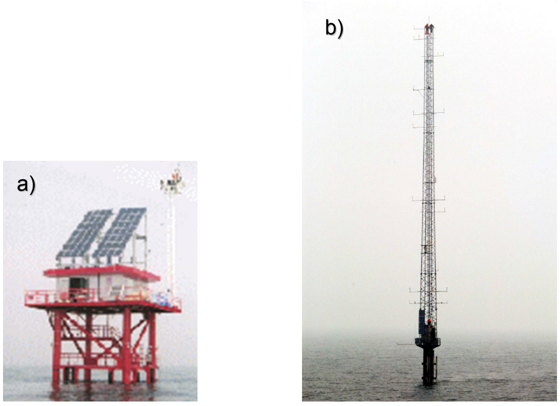

Fig. 2 Offshore wind observation stations; a) a marine tower station in Ise Bay (referred to as MT Station) and b) a meteorological mast at Horns Rev.

30, 45 and 62 m, and vanes are set at 43 and 60 m above sea level (**Fig. 2b**). Additionally, air temperature and water temperature are measured at 13 m and 55m and at the depth of 4 m, respectively. It should be noted that January 2002, data of which is used in this study, is before the wind farm construction and the data have no influences from wind turbines.

The accuracy of simulated wind speeds is evaluated based on three statistics; bias, root-mean-square error (RMSE) and correlation coefficient. Bias indicates the difference between observed and simulated monthly mean wind speeds and the definition is

$$(Bias) = \frac{1}{N}\sum_{i=1}^{N} u_{si} - \frac{1}{N}\sum_{i=1}^{N} u_{oi} \ ,$$

where N is a total number of hourly data, u_{oi} and u_{si} are the observed and simulated hourly values, respectively. The RMSE corresponds to a standard deviation for the difference between observed and simulated wind speeds at each hour, and it is defined as

$$(RMSE) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(u_{si} - u_{oi}\right)^2} \ .$$

Since the bias and RMSE generally tend to become larger as the mean wind speed increases, relative bias and RMSE, which is the bias and RMSE divided by the observed monthly mean wind speed, are also used for the evaluation. Correlation coefficient is defined as

$$(Correlation\ Coefficient) = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(u_{oi} - \overline{u_o}\right)\left(u_{si} - \overline{u_s}\right)}{\sigma_o \sigma_s}$$

where, $\overline{u_o}$ and $\overline{u_s}$ is the observed and simulated monthly mean wind speeds, respectively, and σ_o and σ_s is standard deviation for each value.

3. Results

3.1 Simulation for Ise Bay

The accuracy of the simulation for Ise Bay is evaluated using observation data from MT Station with an anemometer at 18 m height. The simulated wind at the same height is obtained by interpolating the wind speeds at the lowest two levels of the model (6 m and 30 m) assuming a logarithmic profile. As a result of comparing the observed and simulated wind speeds, **Table 2** summarizes the accuracy of the one year simulation for Ise Bay.

First, the observed annual mean wind speed at MT Station is 5.99 m/s, with the lowest monthly mean wind speed in summer and the highest in winter. The simulated annual variation roughly follows these observed characteristics. However, **Table 2** indicates that all the simulated monthly mean wind speeds are lower than the observed ones. Consequently, bias is always negative through the year, ranging from -1.46 to 0.00 m/s. RMSE and correlation coefficient through the year are 2.14 to 3.11 m/s and 0.52 to 0.82, respectively. Like the bias, the RMSE and correlation coefficient also tend to be better in winter and worse in summer.

In order to compare the difference among months more closely, relative bias and RMSE are especially picked up from **Table 2** and shown in **Fig. 3**. As shown in this figure, the relative bias exhibits the best value in March and the

Table 2 Accuracy of simulated wind speed at MT Station in Ise Bay.

Month	MM5 AVE	OBS AVE	BIAS		RMSE		CORREL
	m/s	m/s	m/s	%	m/s	%	
2001-04	5.26	5.55	-0.28	-5.1	2.31	41.6	0.79
2001-05	4.99	5.28	-0.28	-5.4	2.15	40.8	0.70
2001-06	3.51	4.46	-0.95	-21.3	2.42	54.2	0.58
2001-07	3.28	4.74	-1.46	-30.7	2.58	54.3	0.52
2001-08	4.25	5.46	-1.21	-22.2	2.33	42.7	0.75
2001-09	4.73	5.38	-0.65	-12.0	2.14	39.8	0.78
2001-10	5.27	5.79	-0.52	-9.0	2.52	43.4	0.73
2001-11	5.74	6.12	-0.38	-6.3	2.24	36.5	0.79
2001-12	7.00	7.71	-0.71	-9.3	2.52	32.7	0.82
2002-01	7.78	8.33	-0.55	-6.7	3.11	37.4	0.74
2002-02	6.20	6.59	-0.39	-6.0	2.37	36.0	0.78
2002-03	6.38	6.38	0.00	0.0	2.41	37.7	0.79
Annual AVE	5.37	5.99	-0.62	-10.3	2.44	40.7	0.77

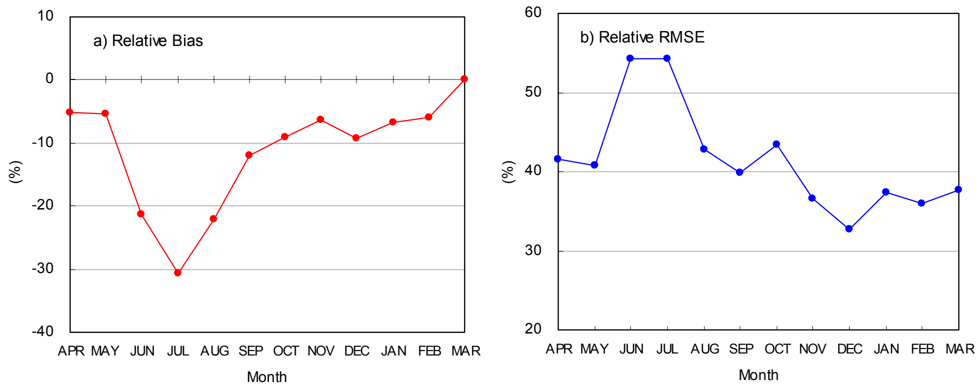

Fig. 3 Annual variation of (a) relative Bias and (b) relative RMSE at MT Station.

worst in July. The relative RMSE is also the lowest in July although the highest occurs in December. **Fig. 3** clearly shows that the simulation accuracy extremely becomes worse in summer months of June, July and August. Except these months, the relative bias is almost less than 10 % and the relative RMSE less than 45 %.

The reason for the bad accuracy in summer may be clearer by looking at **Fig. 4**, which shows the time history of observed and simulated wind speeds in July and December, corresponding to the months with the best and worst relative RMSEs, respectively. A common feature for both months is that the simulation underestimates the wind speed through the whole period. In December, although the simulated wind speed is in a good agreement with the observed one, the two observed peaks seen around 15th and 28th are found not to be well reproduced in the simulation. This kind of error relevant to a synoptic scale forcing is mostly due to the error in the objective analysis used for the lateral boundary condition and four dimensional data assimilation in MM5, and the above errors are not the exception.

A more serious error is the one related to diurnal variation seen in July. It is obviously seen from **Fig. 4a** that the observed wind speed changes on a daily basis, with a maximum during the daytime and a minimum during the nighttime. This is mainly attributed to land-sea breezes and the daytime maximum is mostly caused by the southerly sea breeze. The sea breeze can be also figured out in terms of wind direction, shown in **Fig. 5a**. This figure indicates that the wind direction tends to be south (180º) or south-southeast (157.5º) in the daytime, in spite of the wind direction in the nighttime. Besides in July, a smaller diurnal variation can be also found in December, and the wind direction tends to be north or northeast during the nighttime, although the winter monsoon generally blows from northwest.

As long as seen in **Fig. 5**, it seems that the simulated wind direction can roughly follow the observed tendency of diurnal variation. In contrast, **Fig. 4**, indicates that the simulation does not succeed in well reproducing the diurnal variation of wind speed seen in July. In particular, the daytime peaks caused by the southerly sea breeze are not well simulated and mostly underestimated. These facts mean that the land-sea breeze circulation itself can be partly reproduced in the simulation but the strength is not sufficient. Although the specific causes are not identified in this study, there is no doubt that the better reproduction of the diurnal variation in summer is the key to improving the accuracy of the one year simulation in Ise Bay.

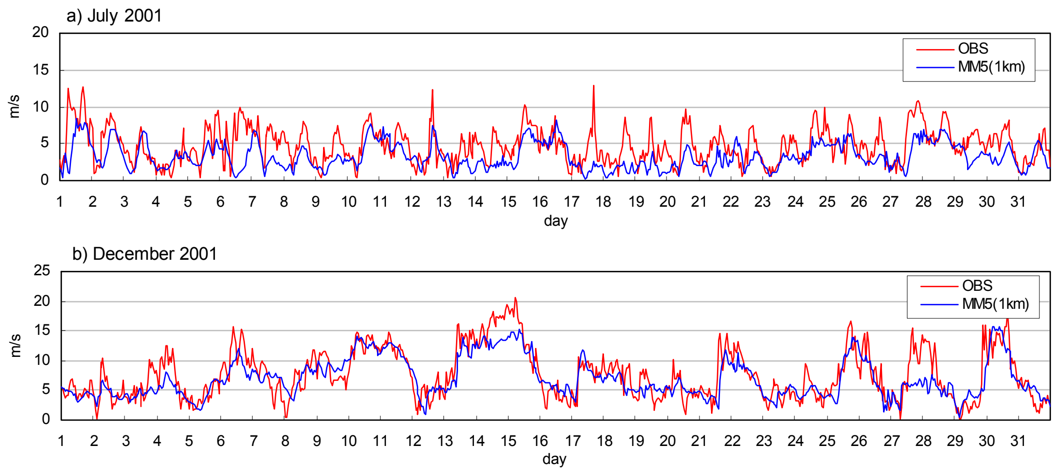

Fig. 4 Time history of observed and simulated wind speeds at MT Station in (a) July and (b) December.

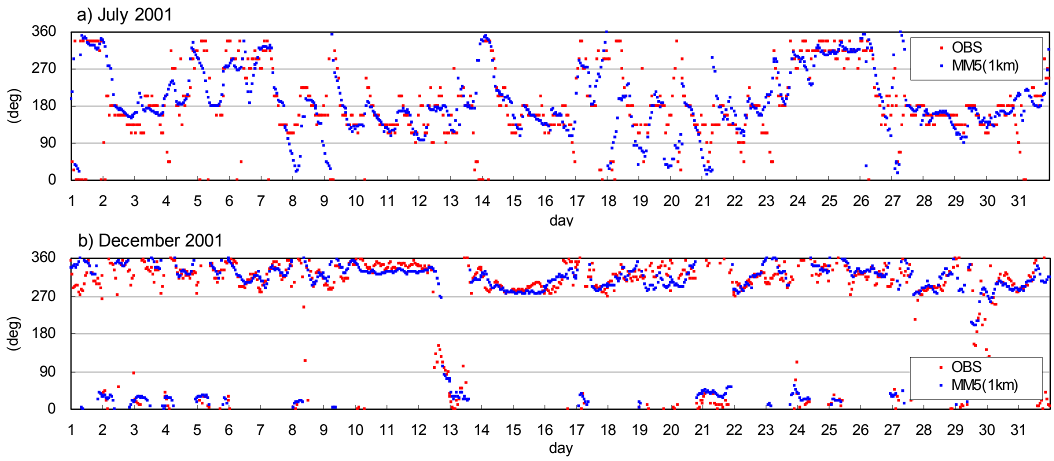

Fig. 5 Same as **Fig. 4**, but for wind direction.

Table 3 Accuracy of simulated wind speed at Horns Rev

Height	MM5 AVE	OBS AVE	BIAS		RMSE		CORREL
	m/s	m/s	m/s	%	m/s	%	
15 m	9.43	9.02	0.41	4.5	1.46	16.2	0.92
30 m	10.14	10.06	0.08	0.8	1.37	13.7	0.94
45 m	10.66	10.64	0.02	0.2	1.37	12.9	0.94
62 m	11.17	11.42	-0.25	-2.2	1.43	12.5	0.95
Average	10.35	10.28	0.07	0.9	1.41	13.8	0.94

3.2 Simulation for Horns Rev

The accuracy of the simulation for Horns Rev is evaluated using observation data from the meteorological mast with anemometers at 15 m, 30 m, 45 m and 62 m heights. The lowest three levels of the model are 11 m, 36 m and 69 m, and the simulated wind speeds at these levels are interpolated to obtain the wind speeds at the four measurement heights. The accuracy of the simulated wind speeds are shown in **Table 3**.

The averages of the observed and simulated monthly mean wind speeds at the mast are 10.35 m/s and 10.28 m/s, respectively, which means a relative bias of only 0.07 m/s on average. For each height, the relative bias ranges -2.2 to 4.5 % with the minimum at 45 m. The RMSEs are 1.37 to 1.46 m/s and the average is 1.41 m/s. The correlation coefficient is 0.94 on average, ranging from 0.92 to 0.95. The high accuracy of the simulation is also suggested in **Figs. 6** and **7**, which show the time history of observed and simulated wind speeds and directions. As indicated in

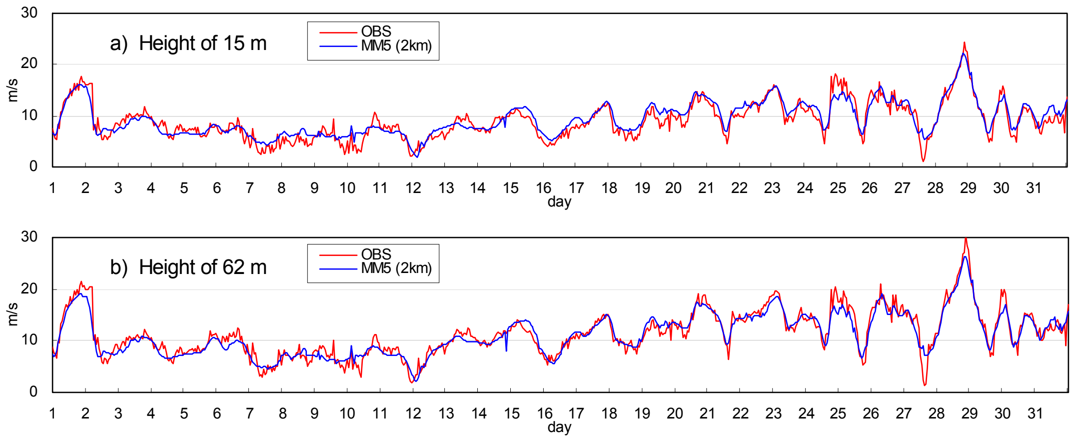

Fig. 6 Time history of observed and simulated wind speed at heights of (a) 15 m and (b) 62 m at Horns Rev.

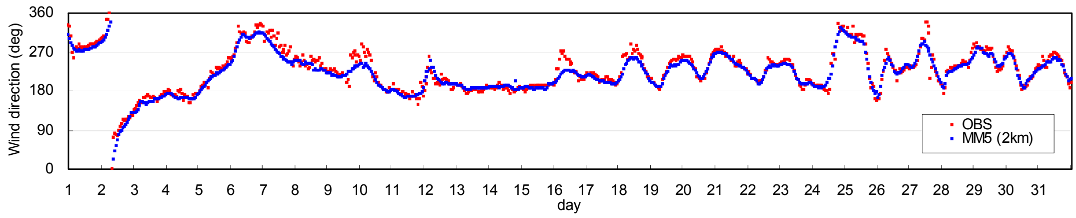

Fig. 7 Time history of observed and simulated wind direction at a height of 60 m at Horns Rev.

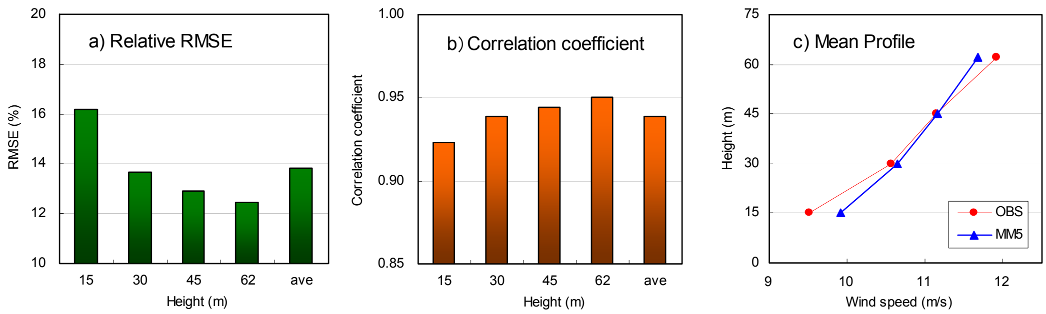

Fig. 8 Comparison of the accuracy of simulated wind speed among four measurement heights at Horns Rev.

these figures, relatively strong southwesterly winds prevail during the simulation period and this means that the wind blows from the sea with a long fetch toward the very flat land in Denmark. This simple condition leads to the good agreement of the simulated winds with the observed ones.

An interesting fact is found in the comparison of the accuracy among heights. In **Fig. 8**, relative RMSE and correlation coefficient are depicted with the mean profile relevant to the relative bias. The relative RMSE is minimum (12.5 %) at 62 m and maximum (16.2 %) at 15 m, and the correlation coefficient has the minimum (0.92) at 15 m and the maximum (0.95) at 62 m. That is, the accuracy of the simulation is found to increase with height. In other words, the accuracy tends to be worse toward the sea surface. It should be also noted that this fact occurs against the mean profile shown in **Fig. 8c**, where the bias is the smallest at 45 m, increasing toward both 15 m and 62 m.

Another important point in the Horns Rev simulation is on the vertical profile of wind speed. As shown in **Fig. 8c**, the simulated monthly mean profile obviously has a steeper gradient than the observed one. In order to examine all of the gradients of the vertical profile at each hour, the ratio between wind speeds at 15 m and 62 m, U_{62}/U_{15}, is chosen as a simple index to represent the profile gradient. The time history is shown in **Fig. 9**, together with the Bulk Richardson number calculated using wind speed at 15 m and air temperature at 13 m and water temperature at -4 m. According to the Bulk Richardson number based on the observation, it is found that there were three major unstable periods in

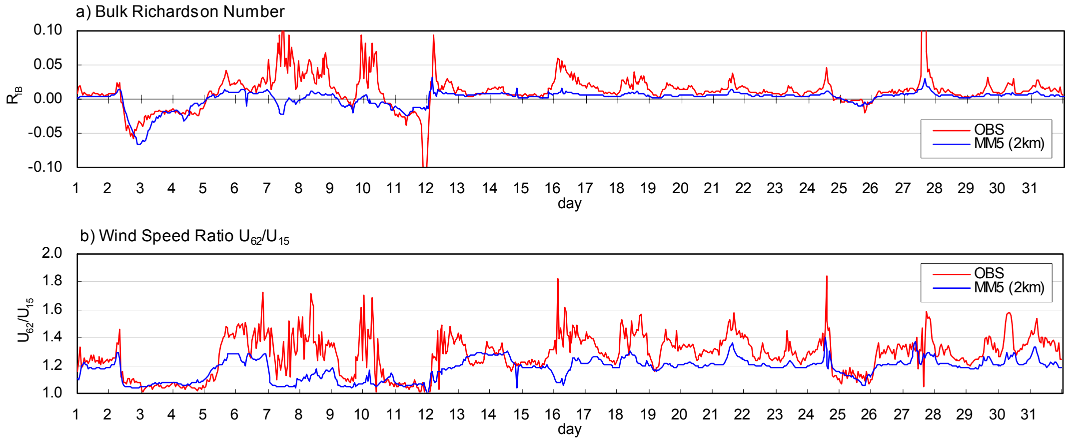

Fig. 9 Time history of a) Bulk Richardson number and b) the ratio of wind speed at 62 m to that at 15 m at Horns Rev.

January 2002; 2nd to 5th, 10th to 12th and 25th to 26th. During these unstable periods, the ratio U_{62}/U_{15} decreases down to around 1.1 and this tendency is well reproduced in the simulation. In contrast, during stable periods, the simulated ratio U_{62}/U_{15} is found to mostly be lower than the observed ratio. This means that the simulated wind profile tends to be steeper than observed one particularly in the stable conditions.

From **Fig. 9a**, it is suggested that the steeper profile found in the simulation partly results from a small Bulk Richardson number during the stable periods in the simulation. This is certainly true, because the NCEP SST used for the lower boundary condition tends to be mostly 1 to 2 degrees higher than the observed water temperature. However, even if the observed water temperature is used as input for MM5 instead of the NCEP SST, the small Bulk Richardson number is still found in the simulation (not shown here). This fact probably means that there is a problem in the physics processes represented in the surface or PBL schemes in MM5, and fixing this problem would lead to improvement of the simulated vertical profile. Associated results on the Horns Rev simulation will be descried in depth in our other paper which will be published soon.

4. Discussion

The obtained results from the two simulations for Ise Bay and Horn Rev indicate that the accuracy of the Ise Bay case is considerably worse than that of the Horns Rev case. Here, the biases, RMSEs and correlation coefficients of the MT Station in January and the height of 15 m at Horns Rev are represented again, picking up the values from **Tables 2** and **3**. Those of the Ise Bay case are -0.55 m/s (-6.7 %), 3.11 m/s (37.4%) and 0.74, while those of the Horns Rev case are 0.41 m/s (4.5 %), 1.46 m/s (16.2 %) and 0.92. As long as comparing these values, it is evident that the accuracy of the simulation for Ise Bay is worse than that for Horns Rev, although January is the month with the highest wind in Ise Bay. In terms of the relative RMSE (%), it can be said that the accuracy of the Ise Bay case is more than twice as bad as that in the Horns Rev case.

An obvious reason for this bad accuracy is the wind direction. In Ise Bay, the primary wind direction is northwest due to the winter monsoon, and the secondary is southeast due to the summer monsoon. As shown in the wind rose in **Fig. 10**, the westerly-to-northerly winds account for more than 60 % of the annual wind direction. A crucial point is that there are mountains with altitudes of more than several hundred meters to the northwest of Ise Bay (**Fig. 11**). That is, the strong winds in the winter always blow from this direction and consequently are greatly affected by the mountains. This causes much fluctuated features in the time history of wind speed in winter shown in **Fig. 4b**, and leads to the worse accuracy in the Ise Bay case, compared to the Horns Rev case.

Another significant reason concerns the diurnal variation of wind speed, which especially prevails in summer. **Fig. 12** shows the diurnal variations of observed and simulated winds at MT station and Horns Rev. These diurnal variations are yield by averaging the time series of the original hourly wind speed minus the 25-hours running mean, in order to eliminate the variations with longer periods than a day. In the Horns Rev case (15 m height), the minimum wind speed appears during the daytime and the maximum during the nighttime. Previous studies (e.g., [7]) show that this kind of diurnal variation is generally seen in coastal waters, and also the feature is substantially reproduced in the simulation.

The observed diurnal variation in January at MT Station is found to resemble that of the Horns Rev case. In contrast, the corresponding simulated diurnal variation has the minimum in the morning and the maximum in the late evening. That is, the phase of the simulated diurnal variation is considerably different from the observed one. On the other

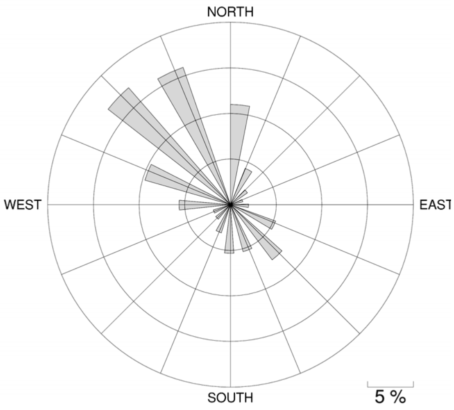

Fig. 10 Wind rose at MT Station in the year from April 2001 to March 2002.

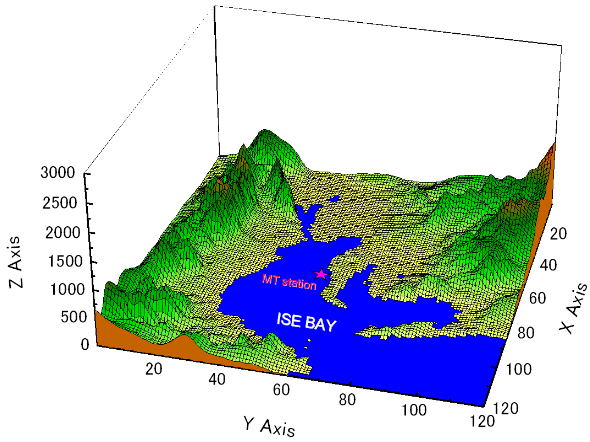

Fig. 11 Terrain around Ise Bay

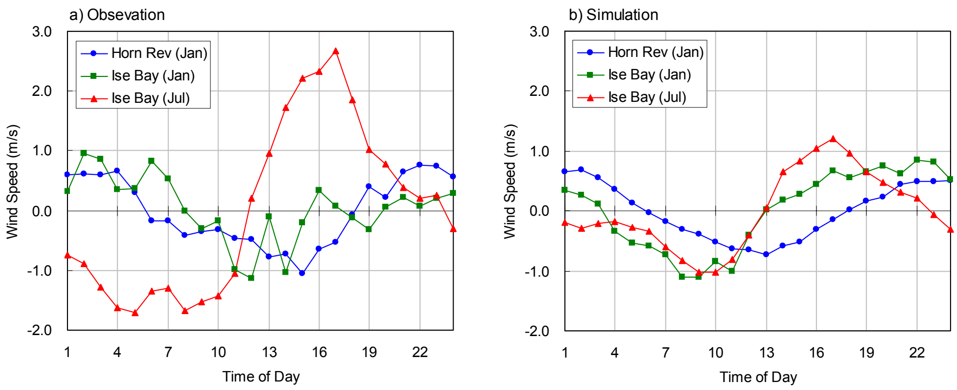

Fig. 12 Diurnal variations of a) measured and b) simulated wind speed at Ise Bay (January 2002 and July 2001) and Horns Rev (January 2002).

hand, in the case for July, the observed diurnal variation has larger amplitude than that of January, and the late afternoon peak due to the southerly sea breeze is outstanding. In this July case, the simulated diurnal variation has a similar phase to the observed one, but their amplitudes are quite different and the simulated amplitude is only a half of the observed one.

It seems that there are some possible reasons for these errors regarding the diurnal variation. They are 1) the effect of four dimensional data assimilation with the objective analysis representing only weak diurnal variations, 2) underestimation of the difference between land and sea surface temperatures in given lower boundary conditions, 3) insufficient representation of physics in the surface or PBL schemes, and so on. Considerations on these points are necessary in future works, in order to improve the accuracy of offshore wind resource assessment with a mesoscale model for the Japanese coastal waters, where the diurnal variation prevails remarkably.

5. Conclusions

In this paper, long-term offshore wind simulations with the mesoscale model MM5 were performed for Ise Bay in Japan and Horns Rev in Denmark, and the accuracy was evaluated using in-situ measurements at both sites. Main obtained results are as follows.

1) In the simulation for Ise Bay, the evaluation using measurements at MT Station (18 m height) shows that biases of monthly mean wind speeds are -1.46 to 0.00 m/s (-30.7 to 0.0 % of the mean wind speed), root-mean-square errors (RMSEs) are 2.14 to 3.11 m/s (32.7 to 54.3 %), and correlation coefficients are 0.52 to 0.82.

2) In the simulation for Horns Rev, the biases, RMSEs and correlation coefficients for four anemometers on a meteorological mast (10 m, 30 m, 45 m, and 62 m heights) are -0.25 to 0.41 m/s (-2.2 to +4.5 %), 1.37 to 1.46 m/s (12.5 to 16.2 %) and 0.92 to 0.95, respectively.

3) Comparing the accuracies of simulated wind speeds at MT Station in January and at the height of 15 m on the

Horns Rev met. mast, all the statistics are worse in the Ise Bay case than in the Horns Rev case. In terms of the relative RMSE (%), the accuracy of the simulation for Ise Bay is more than twice as bad as that for Horns Rev.

4) The worse accuracy for Ise Bay compared to Horns Rev is primarily attributed to prevailing northwesterly winds disturbed by upstream lands and mountains. In addition, insufficient reproduction of the diurnal variation of wind speed in MM5 also makes the accuracy of the simulation be worse, compared to Horns Rev, where the diurnal variation is not so outstanding.

5) Comparison with observed vertical profiles of wind speed at the Horns Rev met. mast shows that the vertical profiles simulated by MM5 using the Eta Planetary boundary layer scheme tend to be mostly too steep with a weak vertical wind shear. This tendency is particularly outstanding in the stable conditions.

Acknowledgment

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