Accuracy of the Wind Speed Profile in the Lower PBL as Simulated by the WRF Model

Susumu Shimada, Teruo Ohsawa, Saaya Chikaoka, and Katsutoshi Kozai
Graduate School of Maritime Sciences, Kobe University, Kobe, Japan

Abstract

Wind resource assessment for coastal areas requires accurate wind speed simulations using a mesoscale model. Our previous study found that the annual mean wind speed simulated by the advanced research Weather Research and Forecasting (WRF-ARW) model has a remarkable positive bias in the lower part of the planetary boundary layer (PBL). This result was obtained from a comparison with wind profiler measurements at Mihama, which is an observation station of the Wind profiler Network and Data Acquisition System (WINDAS) operated by the Japan Meteorological Agency (JMA). In this study, we examine whether such a positive bias can be seen at other WINDAS stations from a comparison of the WRF-simulated wind speed profile using the Mellor-Yamada-Janjic (MYJ) PBL scheme with wind profiler measurements at ten WINDAS stations. The results show that the positive bias is found at all stations, and, moreover, that the positive bias is unlikely to be caused by either error in wind profiler measurement or the objective analysis data input into WRF. In addition, we compare the wind speed profiles simulated by WRF with seven different PBL schemes for a month. The result shows that the positive bias cannot be simply reduced by using other PBL schemes.

1. Introduction

Offshore wind resource assessment using a mesoscale model is a useful method for regional scale site assessment. In order to evaluate the reliability of mesoscale models, the authors have examined (Shimada and Ohsawa 2011) the accuracy of wind speeds simulated by the advanced research Weather Research and Forecasting (WRF-ARW) model (Skamarock et al. 2008; hereafter WRF), which is a fully compressible, non-hydrostatic mesoscale model developed by the National Center for Atmospheric Research (NCAR) and the National Center for Environmental Prediction (NCEP). Using the WRF model, Shimada and Ohsawa (2011) calculated annual mean wind speeds in the coastal area around Shirahama in Tanabe Bay, Japan, and showed that the simulated surface wind speed has a large positive bias at the Shirahama offshore research platform. They also showed that the positive bias is found not only at the surface but also in the lower part of the planetary boundary layer (PBL), from comparison with wind profiler measurements at Mihama, which is an observation station of the Wind profiler Network and Data Acquisition System (WINDAS) operated by the Japan Meteorological Agency (JMA) (Ishihara et al. 2006).

The accuracy of wind speed profiles simulated by mesoscale models in the PBL has been examined using sonde measurements and remote sensing techniques in previous studies (e.g., Zhang and Zheng 2004; Hayashi et al. 2008; Hu et al. 2010). Hayashi et al. (2008) examined the accuracy of wind speed profiles simulated by the JMA non-hydrostatic model (NHM) and WRF using sonde measurements at several stations in eastern Asia. Their results identify a positive bias similar to that found by Shimada and Ohsawa (2011) in the wind speeds simulated by both JMA NHM and WRF. On the other hand, Hu et al. (2010) compared the accuracy of wind speed profiles simulated by WRF using three different PBL schemes. They showed that the wind speed simulated by WRF using the Mellor-Yamada-Janjic (MYJ) PBL scheme (Janjic 1994) overestimates wind speeds compared to measurements near the surface for both stable and unstable conditions. These previous studies indicate that wind speeds simulated by WRF possibly have a positive bias near the surface. Since the accuracy of wind speeds simulated by mesoscale models depends strongly on the validation conditions (e.g., location, period, boundary conditions and model settings), there is considerably uncertainty about whether this positive bias always occurs in the WRF simulations or only under specific conditions. Since wind energy is proportional to the cube of wind speed, the bias in annual mean wind speed is a crucial parameter for offshore wind resource assessment (Shimada and Ohsawa 2011) and it is thus worthwhile to focus on this positive bias to see if a solution to eliminate it from the WRF wind simulation can be found. Therefore, this paper aims to examine whether the large positive bias is peculiar to Mihama or if it can be seen at other measurement sites from WINDAS as well. Moreover, possible causes of the large positive bias are also discussed.

2. Data and methods

2.1 WRF model

The simulation is performed using WRF-ARW version 3.3 for one year from January to December 2005 with one domain covering the west part of Japan, where most WINDAS stations are located near the coast. The model configuration and domain used in the WRF simulation are shown in Fig. 1 and Table 1, respectively. Horizontally, the domain consists of 190 × 159 grid cells with a 3 km cell resolution, and 40 vertical levels are configured between the surface and the 50 hPa pressure level. The vertical grid-size decreases towards the surface, and the heights of the lowest three levels are about 12, 39 and 74 m, respectively. The JMA Meso Analysis (MANAL) data, which is 6-hourly, 10 km × 10 km, 20-level objective analysis data, is used for the four-dimensional data assimilation (FDDA) as well as initial and lateral boundary conditions. Besides, soil temperature and moisture data obtained from the NCEP Final Analysis (2° × 1°, 6-hourly, http://dss.ucar.edu/datasets/ds083.2) (NCEP FNL) is used for the Noah land surface model. The FDDA is performed using the grid nudging technique in the WRF model. In this simulation, the FDDA is applied to the levels above a height of 2,000 m, where the two horizontal wind components, temperature and specific humidity simulated by WRF are nudged toward MANAL. As for Sea Surface Temperature (SST), the daily MODerate resolution Imaging Spectroradiometer (MODIS)-based SST composite with 0.02° × 0.02° grid cells is used as the lower boundary condition. The primary physics options, selected by reference to Suselj and Sood (2010), are also shown in Table 1. The MYJ PBL scheme, which is widely used for wind resource assessment with mesoscale
3. Results and discussion

3.1 Wind speed bias at ten wind profiler stations

Firstly, we examine whether the large positive bias in the lower PBL found at Mihama in our previous study (Shimada and Ohsawa 2011) is evident at other WINDAS stations. The hourly model output, which is linearly interpolated to the wind profiler measurement height, is compared with the ten-minute averaged WINDAS wind speed at each height. Here, the WRF-simulated wind speed profile taken from the land grid cell and vertical height corresponding best to the location of the WINDAS observation station was compared to the measurements. Although the surface level height of each WRF grid was not necessarily identical to the observation station heights, since the maximum difference of height between the WRF grids and the WINDAS stations is 45 m, the correction for the difference is not performed in this validation.

Figure 2 shows vertical profiles of annual mean wind speed from WINDAS and the bias in the WRF wind speed at all stations. Here, the word “bias” means the value of an annual mean “simulated” wind speed minus an annual mean “measured” wind speed. In order to reduce the difference originating from on-site conditions, the relative value normalized by the measured wind speed is frequently used for the evaluation of the accuracy of wind speed simulated by a numerical model in wind resource assessment (Lange and Focken 2006). Thus relative values (%), defined as the bias divided by the mean measured wind speed at each height, are shown as well as absolute bias.

In Fig. 2, the absolute biases at most stations are found to have slightly negative values at levels higher than 4,000 m, and the biases exhibit negative peaks at a height of approximately 2,500 m. Between 1,300 m and 2,500 m, the bias changes the sign to positive and increases toward the surface at all stations. At the lowest level (400 m), the positive bias at each station reaches up to +1.0 to +2.7 m s\(^{-1}\) (+12 to +83% of mean measured wind speed). In short, the large positive bias in the lower PBL can be clearly seen at not only Mihama but also at all nine other stations.

Since mesoscale model simulations with a few kilometers spatial grid resolution cannot entirely reproduce undulations in actual topography, the simulated wind speeds near the surface can be expected to have a large negative or positive bias due to the coarse topographic representation in the model. Nevertheless, the biases at all ten stations in Fig. 2 exhibit positive values as well as results shown in previous studies. Thus these results suggest that the large positive bias found in the WRF wind speed is more likely to be caused by systematic error in the WRF model itself rather than the model settings. It is also found that the positive bias in the lower PBL tends to be larger when the simulated wind speed has a more remarkable negative peak in bias in the upper PBL. If this result is associated with an overestimation of vertical mixing within the PBL, this would suggest the possibility of systematic error in the models (e.g., Jimenez et al. 2007; Suselj and Sood 2010; Hasager et al. 2011), is at first selected for the validation. The performance of other PBL schemes implemented in the WRF-ARW is then tested.

2.2 Data used in the validation

Vertical profiles of wind speed simulated by WRF are compared with measurements from WINDAS at ten stations. The WINDAS measures wind speed at the heights from 400 to 9,000 m AGL at intervals of 300 m, based on the Doppler effect from electromagnetic radiation beams in five directions. The ten-minute averaged measurements are used in this validation. WINDAS presently operates 31 observation stations in Japan, and this study uses the data from ten stations: Nagoya, Owase, Mihama, Tottori, Hamada, Takamatsu, Kochi, Shimizu, Oita and Nobeoka. The locations of these stations are shown in Fig. 1. In addition, wind speeds measured from the JMA rawinsonde at Yonago and Shionomisaki are also used in this validation.

Table 1. WRF configuration.

<table>
<thead>
<tr>
<th>Period</th>
<th>Input data</th>
<th>Domain</th>
<th>Physics options</th>
<th>FDDA option</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start: 00:00 UTC 1st Jan 2005</td>
<td>JMA MANAL (6-hourly, 10 km × 10 km)</td>
<td>3 km (190 × 159 grids)</td>
<td>Dudhia short wave radiation, RRTM long wave radiation, Eta microphysics, Betts-Miller-Janjic cumulus parameterization, Noah land surface model, MYJ PBL parameterization</td>
<td>Enabled above 2000 m height.</td>
</tr>
<tr>
<td>End: 24:00 UTC 31st Dec 2005</td>
<td>NCEP FNL (6-hourly, 1° × 1°)</td>
<td>Vertical layer: 40 levels (surface to 50 hPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MODIS-based SST (daily, 0.02° × 0.02°)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Simulation domain and observation stations.

Fig. 2. Vertical profiles of (a) measured mean wind speed, (b) absolute bias, and (c) relative bias in the WRF wind speed at ten wind profiler stations in the year 2005.
Fig. 3. Vertical profiles of (a) absolute and (b) relative bias averaged for ten stations for each month.

eddy viscosity coefficient in the MYJ scheme.

As mentioned in Sect. 1, Hayashi et al. (2008) and Hu et al. (2010) also found a similar positive bias in the WRF-simulated wind speed profile near the surface from a comparison with measurements for a few summer months. This finding raises the question whether the positive bias in the annual mean wind speed is mainly attributable to the bias in the summer season. Thus, the bias in each month is examined. Figure 3 shows vertical profiles of the monthly bias averaged for the ten stations. From Fig. 3, the positive bias in the lower PBL can be seen in all months. At the lowest level, the bias ranges from +1.4 to +2.3 m s\(^{-1}\) (from +32 to +46% of monthly mean wind speed). Any tendency that summer months particularly exhibit a large positive bias cannot be clearly identified from Fig. 3.

3.2 Possible causes of the positive bias

The JMA WINDAS measures wind speed in a unit of 1 m s\(^{-1}\), which is comparable to the value of the bias between the WRF-
simulated and the measured annual mean wind speeds. Moreover, there might be some influences from ground or artificial and ter-
restrial objects around the wind profiler, which can affect the wind speed measurement based on remote sensing observation and lead to positive bias. Thus, we next compare the WRF wind speed profile to the profile measured with a rawinsonde, which is based on in situ observation. 12-hourly data for the year 2005 is used for the comparison. Figure 4 shows vertical profiles of the bias in the WRF wind speed at two rawinsonde observation stations: Yonago and Shionomisaki. Both stations exhibit positive biases in the lower PBL, similar to the bias found using WINDAS. This result indicates that the positive biases found in Fig. 2 are not likely to be caused by some error in the wind profiler measurements.

Another possible cause of the positive bias is some influence from JMA MANAL, which is the objective analysis data used for FDDA and initial and boundary conditions in the WRF simulation. If MANAL originally has a positive bias, WRF could also have a positive bias. We thus examine the profiles from MANAL in the same way as Fig. 2. Figure 5 shows vertical profiles of the bias in the MANAL wind speed at ten stations. Here, in order to easily handle the MANAL data, 6-hourly MANAL wind speeds are hori-
zontally and vertically interpolated onto the WRF grid cells using the WRF pre-processing packages. In Fig. 5, the MANAL wind speed does not have a large bias at most stations except for Owa-
see and Kochi. Even at these two stations, the absolute biases are relatively small and the relative biases do not increase simply with a decrease of height, unlike the WRF biases. Since JMA opera-
tionally assimilates the wind profiler data to MANAL, this result seems reasonable to some extent. Thus, the positive bias found in the WRF wind speed is speculated not to be caused by the FDDA with MANAL.

3.3 Effects of the PBL scheme on the vertical wind profiles

From a comparison of wind speed profiles simulated by WRF using three different PBL schemes, Hu et al. (2010) reported that the positive bias is clearly found only when using the MYJ PBL scheme. In contrast, from a comparison of wind profiles simulated by MM5 (Grell et al. 2004) using different five PBL schemes, including the MYJ scheme, Zhang and Zheng (2004) concluded that the simulated wind speed profiles have little dependence on the PBL scheme except near the ground. In fact, in Hayashi et al. (2008), a positive bias can be seen in the result obtained from the WRF simulation using the Yonsei University (YSU) PBL scheme. If the result shown in Hu et al. (2010) can be entirely applied to the WRF simulation in Japanese coastal water areas, the posi-
tive bias found in Fig. 2 could be removed by the use of another PBL scheme in WRF. In the latest version of WRF-ARW (version 3.3 updated in April 2011), ten PBL schemes based on different PBL parameterizations are available. The features of these PBL

Table 2. PBL schemes available in WRF-ARW ver. 3.3.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Turbulence closure order</th>
<th>Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td>YSU</td>
<td>1.0</td>
<td>Non-local-K scheme with explicit entrainment layer and parabolic K profile in unstable mixed layer</td>
</tr>
<tr>
<td>MRF</td>
<td>1.0</td>
<td>Older version of the YSU scheme</td>
</tr>
<tr>
<td>ACM2</td>
<td>1.0</td>
<td>Asymmetric Convective Model with non-local upward mixing and local downward mixing</td>
</tr>
<tr>
<td>BouLac</td>
<td>1.5</td>
<td>Designed for use with BEP (Building Environment Parameterization) urban model</td>
</tr>
<tr>
<td>MYJ</td>
<td>1.5</td>
<td>One-dimensional prognostic turbulent kinetic energy scheme with local vertical mixing</td>
</tr>
<tr>
<td>QNSE</td>
<td>1.5</td>
<td>A TKE-prediction option that uses a new theory for stably stratified regions</td>
</tr>
<tr>
<td>TEMF</td>
<td>1.5</td>
<td>Sub-grid total energy prognostic variable, plus mass-flux type shallow convection</td>
</tr>
<tr>
<td>UW</td>
<td>1.5</td>
<td>TKE scheme from NCAR CESM (Community Earth System Model) climate model</td>
</tr>
<tr>
<td>MYNN2</td>
<td>1.5</td>
<td>Predicts sub-grid TKE terms</td>
</tr>
<tr>
<td>MYNN3</td>
<td>2.0</td>
<td>Predicts TKE and other second-moment terms</td>
</tr>
</tbody>
</table>
schemes are summarized in Table 2, by reference to the WRF-ARW users’ guide (available at http://www.mmm.ucar.edu).

Thus, we finally examine whether the positive bias can be reduced by the use of other PBL schemes in the WRF model. These additional simulations use the model configuration identical to that shown in Table 1 except for the PBL scheme and its associated surface layer scheme. Here, the BouLac scheme developed for an urban canopy model and the MRF scheme, which is the older version of the YSU scheme, are excluded from the validation. In addition, since the simulation using the MYNN3 schemes did not run correctly due to unexpected error on our cluster system, the MYNN3 scheme was also excluded from the validation. The seven simulations are performed for the month of January 2005. Figure 6 shows the comparison of the vertical bias profiles averaged for ten stations from the WRF simulations with the YSU, MYJ, QNSE, MYNN2, ACM2, UW and TEMF PBL schemes. The positive bias in the lower PBL can be seen in the wind speed simulated with other PBL schemes as well as the MYJ scheme. From a one-month comparison, we found that the positive bias in the WRF wind speed using the MYJ scheme cannot be simply removed by using other PBL schemes.

In additional studies, we have already examined the impacts of the accuracy of SST, horizontal grid resolution and the surface roughness length on the accuracy of the WRF-simulated wind profiles. However, we have not yet found evidence that these settings directly lead to the positive bias in the lower PBL (figures not shown). At the moment, we therefore conclude that the positive bias is most likely caused by a deficiency in the WRF model itself, such as the deficiency in the formulation of PBL or surface layer parameterization rather than the accuracy of external data input into WRF and the model settings.

4. Conclusions

The accuracy of vertical wind speed profiles simulated by WRF was investigated in comparison with wind profiler measurements taken from the JMA WINDAS. The main conclusions obtained in this study are summarized as follows:

1. From the comparison with measurements at ten stations, the WRF-simulated wind speed profile has positive biases in the lower part of PBL at not only Mihama, as shown in our previous study, but also at all other stations.

2. Comparison with rawinsonde measurements at two stations also shows similar positive biases in the lower PBL. It is thus unlikely that the positive bias is due to error in the wind profiler measurements.

3. It is moreover found that JMA MANAL, used as input for WRF, has much smaller biases in the lower PBL at most stations than the WRF wind speed, and therefore the positive bias is likely not caused by the four dimensional data assimilation with MANAL.

4. From the comparison of vertical profiles of monthly bias at ten stations, the bias in the lower PBL is found in every month through the year.

5. From the comparison of vertical profiles of monthly bias from the WRF simulations with different PBL schemes, the positive bias can be seen in the WRF wind speed using other PBL schemes as well as the MYJ scheme.

In summary, the causes of the positive bias are not clearly identified in this study. However, the above facts suggest that the positive bias is attributed to the WRF model itself and is recognized as a systematic error in the model. We therefore suggest that further study is required for identifying the cause of and removing the positive bias in the WRF wind simulation, because this bias in wind speed can greatly affect the accuracy of wind resource assessment.

Acknowledgements

The authors are grateful to the chief editor, Dr. Yoshizaki, and anonymous reviewers for their constructive comments. This study was supported by a Grant-in-Aid for Scientific Research (B) 22360379 and the Promotion of Sciences Fellows 2169111 from the Ministry of Education, Science, Sport and Culture, Japan. The MODIS product was obtained from the Japan Aerospace Exploration Agency.

References


Manuscript received 30 March 2011, accepted 23 June 2011
SOLA: http://www.jstage.jst.go.jp/browse/sola

Fig. 6. Vertical profiles of bias averaged for ten stations from the WRF simulations with seven PBL schemes for January, 2005.