Journal of Mechanical Science and Technology 24 (10) (2010) 2017~2023
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-010-0613-z

# Application of wind data from automated weather stations to wind resources estimation in Korea

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(Manuscript Received September 10, 2009; Revised March 26, 2010; Accepted June 1, 2010)

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## Abstract

The wind data measured from automated weather stations (AWS) at complex terrain in Korea was used to predict the wind speed at nearby sites that are several kilometers away. The 10-minute averaged wind data was measured at a height of 10 meters. A commercial CFD code, WindSIM, based on the Reynolds averaged Navier-Stokes equation was employed. The results were compared with the data measured using meteorological masts (MM) at heights of 30 to 50 meters installed for this study. The predictions using the AWS data and WindSIM showed good agreements with the measured data. The results are expected to be useful to find out a spot to install a meteorological mast for future wind farm development in complex terrain.

*Keywords*: Wind prediction; AWS; Complex terrain; WindSIM

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## 1. Introduction

More evaluations of the wind resource in complex terrain than those in flat terrain are required because the wind resource increases with altitude [1]. For this reason, a lot of researches on the analysis and prediction of wind resources have been performed in complex terrain [2-4]. There are two programs that are commonly used for wind resource analysis and prediction all over the world. These are WAsP [5] and WindSIM [6]. WAsP(Wind Atlas Analysis and Application Program) based on a linear model known as BZ model is known to be good for wind resource analysis and prediction in flat terrain. However, it might not be so good in complex terrain because the flow separation phenomenon is not considered in the program [7, 8]. WindSIM is a CFD (Computational Fluid Dynamics) code. It solves the Reynolds averaged Navier-Stokes (RANS) equation using the standard k-ε turbulence model and obtains three dimensional flow fields. It is considered proper for predicting wind resource in complex terrain [9-12]. WindSIM has been, however, seldom used for estimating wind resource in complex terrain in Korea although it is considered necessary to be done [11].

There exist about 580 weather stations that measure wind speed and direction in Korea. The oldest one has been performing measurement for more than 100 years. They have been mainly used for a real time monitoring for severe weather. Due to the low quality of the data mainly resulting from the low measurement height, they were not used for predicting wind resources for nearby sites although they are easily accessible. No research has been, however, performed in Korea on the possibility of using them for predicting wind resource in complex terrain.

In order to find a good place to construct a wind farm, it is essential to install a meteorological mast and monitor the wind speed and direction for at least a year. Then the measured data is used to draw a wind resource map around the mast to find a good place to locate wind turbine generators. It is, however, not an easy task to find a proper spot for the mast to be installed where the wind energy should be high. If the data obtained from weather stations is good enough to predict wind speed in complex terrain, it can be conveniently used to find a spot where the meteorological masts will be installed.

In this study, wind velocities at six sites close to six different weather stations and located in complex terrain in Korea are predicted using the data measured by nearby AWS (Automated Weather Station) to find out if the data from AWS can be used to predict wind speed in complex terrain. The prediction of wind speed is made by WindSIM and the result is compared with the measured data obtained from meteorological masts installed for this study for validation. The possibility using the AWS data for predicting wind speed of the sites in complex terrain is then evaluated.

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[†] This paper was recommended for publication in revised form by Associate Editor Haecheon Choi

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## 2. Input data

### 2.1 AWS and prediction sites

Six sites (A, B, C, D, E, F) located in complex terrain were analyzed using WindSIM in this study as shown in Fig. 1. The measurement data obtained by the closest AWS's (A*, B*, C*, D*, E* F*) to the sites was used to predict the wind speed at each site. The predictions were compared with the measured wind velocities at the sites.

The altitudes of the AWS sites and prediction sites from the sea level and their distances are presented in Table 1. The AWS sites are mostly located in lower altitudes than the prediction sites except E*. The Sites C*, E* and F*are located on the ridge of a mountain. The distances between the prediction sites and their AWS sites were ranged from 7.5 km to 13.9 km.

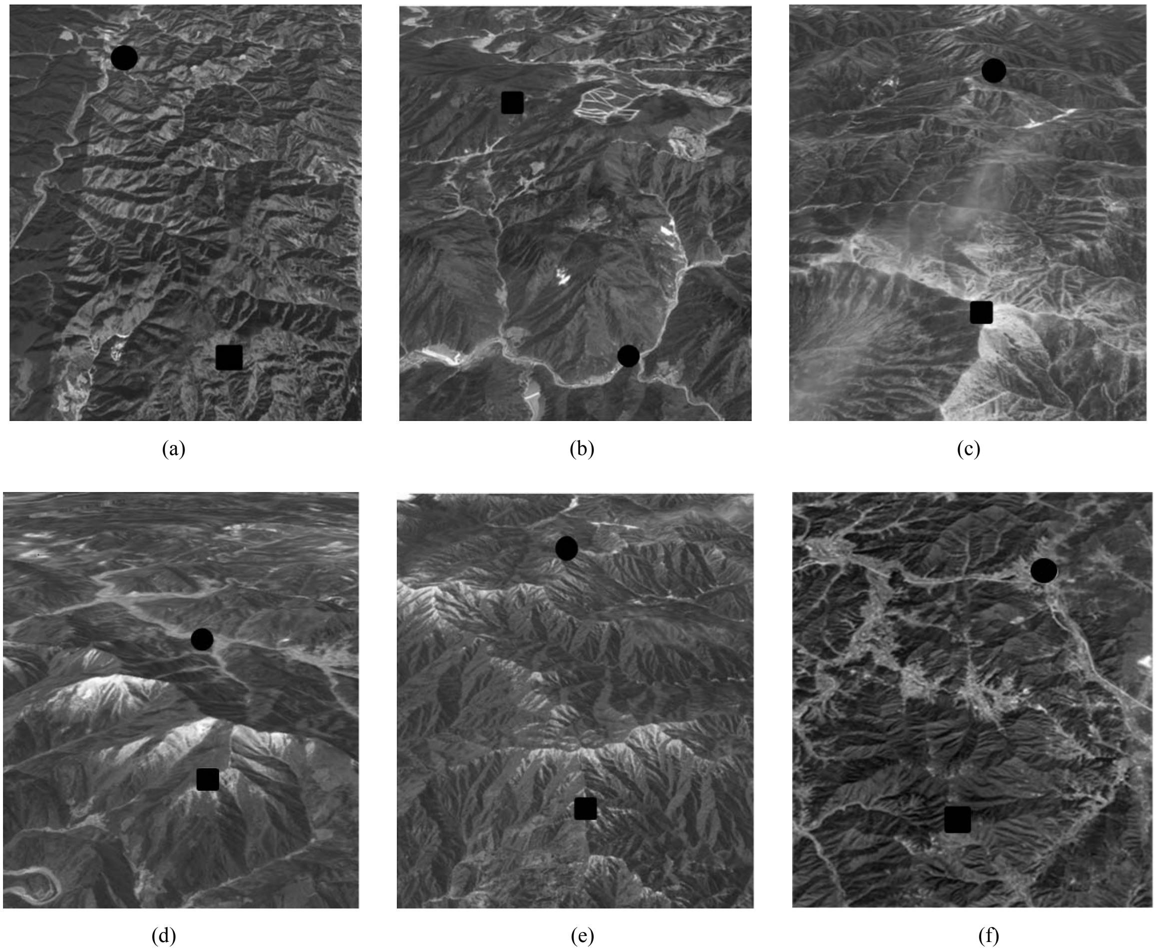
### 2.2 AWS and measurement data

For the prediction, the data measured for more than six months from AWS at a height of 10 m from ground was used as an input to WindSIM. In order to validate the predictions from WindSIM, 30 m to 50 m high meteorological masts were installed for this study to measure 10 minute averaged wind speed and direction. The measurement period and height of mast used for each site is provided in Table 2.

Table 3 shows the Weibull representation of measured data at each site. The Weibull probability distribution is known as an accurate representation of a wide variety of wind regimes [13]. The AWS data is converted in WindSIM to Weibull probability distribution function sector by sector and used for solving RANS equation. Total 12 sectors with 30 degrees interval are used [14]. The reason why the 10 minute averaged wind data is converted to Weibull probability distribution function is that it enables to use simple statistical relations to

Table 1. Altitudes and distances between prediction and AWS sites.

| Site | Altitude (m) | Distance (km) |
|---|---|---|
| A-A* | 1190-100 | 13.9 |
| B-B* | 1136-550 | 7.5 |
| C-C* | 1375-1004 | 9.4 |
| D-D* | 1138-450 | 8.1 |
| E-E* | 850-1004 | 10.9 |
| F-F* | 812-235 | 13.0 |


(a) (b) (c)

(d) (e) (f)

Fig. 1. Topographical maps of six sites (AWS:●, Prediction site:■).

Table 2. Measurement period and height of mast.

| Site | Period | Height of mast (m) |
|---|---|---|
| A-A* | 12 months | 40-10 |
| B-B* | 12 months | 40-10 |
| C-C* | 6 months, 23 days | 40-10 |
| D-D* | 12 months | 40-10 |
| E-E* | 12 months | 50-10 |
| F-F* | 12 months | 30-10 |

Table 3. Altitudes and distances between prediction and AWS sites.

| Sites | Wind Speed [m/s] | A [m/s] | c |
|---|---|---|---|
| A-A* | 4.00-0.86 | 4.55-0.99 | 2.32-1.64 |
| B-B* | 5.00-1.29 | 5.45-1.42 | 1.50-1.43 |
| C-C* | 7.06-2.59 | 7.90-2.77 | 1.85-1.40 |
| D-D* | 3.62-1.50 | 4.01-1.45 | 1.55-1.16 |
| E-E* | 5.75-2.89 | 5.94-3.18 | 1.27-1.48 |
| F-F* | 6.73-2.50 | 7.66-2.93 | 1.83-1.71 |

calculate the mean power density as well as the mean and standard deviation of wind speed [13]. The relation between the frequency distribution of the measured wind speed and the Weibull distribution function is obtained using [13]

$$f(V)=\frac{c}{A}\left(\frac{V}{A}\right)^{c-1}\exp\left[-\left(\frac{V}{A}\right)^{c}\right] \tag{1}$$

where V is the wind speed, f is the frequency of occurrence of the wind speed, c is the shape factor and A is the scale factor. The c and A in Eq. (1) to best describe the measurement wind speed and frequency of occurrence are obtained in WindSIM by using minimization technique in numerical methods [15]. As long as the Weibull parameters A and c are obtained, it is possible to calculate the average wind speed using the following Eq. [13]:

$$\bar{V}=A\Gamma\left(1+\frac{1}{k}\right) \tag{2}$$

where $\bar{V}$ is the average wind speed and $\Gamma$ is the gamma function defined as [13]:

$$\Gamma(x)=\int_0^\infty e^{-t}t^{x-1}dt\,. \tag{3}$$

The Weibull-fitted average velocities obtained in WindSIM were ranged from 0.86 m/s to 2.89 m/s for the AWS sites. They were ranged from 3.62 m/s to 7.06 m/s for the prediction sites.

Table 4. Input values for WindSIM.

| Site | Domain Size(km) | Grid Spacing x, y (m) |
|---|---|---|
| A | 12.7 × 24.5 | x:43.5~221.1, y:38.5~195.8 |
| B | 21.9 × 27.5 | x:58.8~294.0, y:57.1~285.5 |
| C | 19.2 × 10.7 | x:40.0~202.2, y:45.4~230.9 |
| D | 15.1 × 19.1 | x:42.8~213.0, y:40.0~201.6 |
| E | 21.6 × 24.6 | x:58.8~294.6, y:57.1~294.0 |
| F | 13.6 × 23.7 | x:43.5~219.7, y:38.5~196.2 |

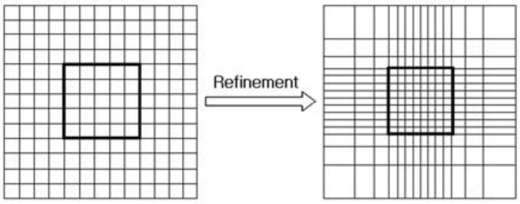


Fig. 2. Schematic of cell refinement.

## 3. Modeling

### 3.1 x-y cell

Table 4 shows the size of the map and cell sizes in x and y directions used for the computer simulation. The positive x and y directions in the map are defined as horizontal directions heading east and north, respectively. The positive z direction is defined as a vertical direction heading upward. As shown in the table, the sizes of the maps are different for different sites because the distance from each AWS to each prediction site is not the same. It was found from a previous study of the authors that the distance between the prediction site and the closest boundary of the topographical map must be larger than about 4 km [16] to minimize the effect of boundary conditions on the solution. Therefore, the distance from the prediction site to any boundary of the map was chosen to be at least larger than 5 km.

For the cell sizes in x and y directions, they are related to the total map size because the number of cells that WindSIM can handle is limited. Therefore, a refinement option in WindSIM to refine the cells in the area of interest was used. The refinement option enables to have a smaller cell size in the area of interest as shown in Fig. 2. If the refinement area is selected in the map, a smaller constant cell size is applied inside the area and the cell sizes gradually get larger as they get further away from the area. If the refinement option is used, a particular region of interest can be modeled in more detail for better accuracy.

Due to the different sizes of the maps for different sites in the study, the cell sizes varied between 38.5m and 58.8 m as shown in Table 4. These cell sizes were considered good enough for wind speed predictions in this study because the wind speed prediction is known to converge in WindSIM when the cell sizes are about or less than 50 m [16].

Table 5. Upper boundary heights of different sites used for WindSIM simulation.

| Site | Height [m] |
|---|---|
| A-A* | 9691.0 |
| B-B* | 4909.0 |
| C-C* | 6363.0 |
| D-D* | 4669.0 |
| E-E* | 8982.0 |
| F-F* | 6814.9 |

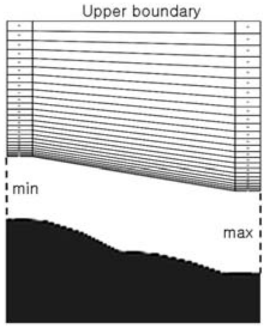


Fig. 3. Schematic of upper boundary with minimum and maximum distance to ground.

### 3.2 z- cell

For the cell size in z direction, it is related with number of cells in z direction and height distribution factor. The height distribution factor is defined as the ratio of the cell size at the ground to that at the upper boundary. In this case, as shown in Fig. 3, the upper boundary is automatically determined by WindSIM high enough to avoid a blocking effect on the wind flow [17] in any locations of the map. The upper boundaries of the six sites are presented in Table 5.

In order to describe the flow field well for the AWS data measured at a height of 10 m from the ground, the number of cells in z direction was set to be 59, which was the maximum value to be used. Also, the height distribution factor was set to be small enough for the same reason. Based on these settings, the heights of 10 cells at both minimum and maximum elevation in z direction are presented in Table 6.

### 3.3 Boundary condition

The three dimensional (3D) calculation domain of WindSIM is determined by the map boundary in x and y directions, and by the ground at the bottom and the atmospheric boundary layer height at the top in z direction. When WindSIM solves the RANS equation, a log profile of wind speed is applied as a boundary condition at the x and y boundary of the 3D calculation domain from ground to atmospheric boundary layer height. This is equivalent to the fact that infinite plain terrain is connected to the boundaries [17].

Table 6. Cell distance in z direction from ground.

| Site | Distance [m] | | | | | |
|---|---|---|---|---|---|---|
| | NO. | 1 | 2 | 3 | 4 | 5 |
| A-A* | Min | 1.6 | 7.7 | 19.2 | 36.4 | 59.1 |
| | Max | 1.8 | 8.4 | 21.2 | 40 | 64.9 |
| B-B* | Min | 0.8 | 3.9 | 9.7 | 18.4 | 29.9 |
| | Max | 1 | 4.9 | 12.3 | 23.2 | 37.7 |
| C-C* | Min | 1.1 | 5 | 12.6 | 23.9 | 38.8 |
| | Max | 1.3 | 5.9 | 14.9 | 28.1 | 45.6 |
| D-D* | Min | 0.8 | 3.7 | 9.3 | 17.5 | 28.5 |
| | Max | 1 | 4.7 | 11.8 | 22.4 | 36.3 |
| E-E* | Min | 1.5 | 7.1 | 17.8 | 33.6 | 54.6 |
| | Max | 1.7 | 8.1 | 20.3 | 38.4 | 62.4 |
| F-F* | Min | 1.1 | 5.4 | 13.5 | 25.6 | 41.5 |
| | Max | 1.3 | 6.2 | 15.6 | 29.6 | 48 |

The atmospheric boundary layer height was assumed to be 500 m, which is known to be the most used by scientists in literature to describe the height of geostrophic wind [18]. Above the atmospheric boundary layer, the wind speed is fixed to be a constant value, 10 m/s. This constant wind speed is applied up to the upper boundary of the solution domain. It is known that the effect of the constant speed of the atmospheric boundary layer on the wind speed prediction is small [18].

The boundary conditions for standard k-ε turbulence model to run the CFD simulation are as follows [18]:

$$f(V) = \frac{c}{A}\left(\frac{V}{A}\right)^{c-1} \mathbf{exp}\left[-\left(\frac{V}{A}\right)^{c}\right], \tag{4}$$

where u is the wind speed, z is the height, c is a constant, and is the height of the boundary layer, and

$$\varepsilon(z) = \frac{u(z)^3}{VKC}\left(\frac{1}{z} + \frac{1}{L_{obu}}\right), \tag{5}$$

where VKC is the Von Karman constant, $L_{obu}$ is the Obukhov length [18].

Also refined cells were used for the area including the prediction sites. Because almost all the sites including the AWS and prediction sites in the map are in mountainous area, a constant roughness length of 0.5m corresponding to the roughness length for forests [19] was used for the entire sites from A to F. It was assumed that there are no obstacles for the simulation.

## 4. Results

Table 7 shows the wind speed predictions as well as the measured wind speeds for all the sites. As shown in the table, the prediction errors were within 15% for all the cases. For sites B, C and F, the errors were smaller than those from the other sites and were less than 4 %. For sites A, D and E, the prediction errors were slightly higher. The average prediction error of the six sites analyzed was within 8 %.

Fig. 4 shows the wind rose prediction and the measured wind rose. For site D, the predicted and the measured wind roses were relatively close. For the other sites, however, they were much different. In case of E, the discrepancy was huge. The reason for the discrepancy is considered due to the fact that the AWS data is normally measured at a height of 10m from the ground and therefore is sensitive to the effect of obstacles and roughness. Also, the average wind velocities measured are mostly less than 3 m/s. Therefore, the measurement data will be vulnerable to wind direction errors. Also the distance between the AWS and the prediction site is larger than 7 km. It seems that comparing the average wind speeds instead of the wind roses has reduced the errors although the error in the wind direction is large.

The result from the study says that although the AWS data cannot be used to accurately predict the wind rose of other nearby sites that are several kilometers away, it is useful enough to be used to find out a spot where the averaged wind speed is relatively higher than other spots. This is very important for investigating wind resource to construct a wind farm at complex terrain in Korea because the AWS data is available over the country and it is open to public. In order to accurately estimate wind resource around a site, a 40 m to 60 m tall meteorological mast is normally used in Korea for wind measurement. The measurement site has commonly been determined by information obtained from the residents who live near the site. This often resulted in installing a meteorological mast at a spot where the wind resource is low. Using the proposed method, good spots for meteorological masts can be obtained easily only if the nearby AWS data is employed. A higher meteorological mast can be installed on that spot to accurately measure the wind speed and direction to be used for micrositing of wind turbine generators.

Table 7. Wind speed prediction.

| Site | Measured | Predicted | Error [%] |
|---|---|---|---|
| A | 4.00 | 3.44 | -14.0 |
| B | 5.00 | 4.90 | -2.0 |
| C | 7.06 | 6.84 | -3.1 |
| D | 3.62 | 4.04 | 11.6 |
| E | 6.57 | 5.80 | -11.7 |
| F | 6.73 | 6.80 | -1.04 |
| Average | | | 7.24 |

## 5. Conclusion

The AWS data measured at a height of 10m from the ground was used to predict the wind speed of nearby sites at complex terrain in Korea. A CFD code, WindSIM, was used. As the result, in terms of wind speed only, the prediction values were close to the measured values. For all six sites, the errors were within 15 %. In terms of wind rose, however, the predictions were much different from the measured values. The reason is considered inherent and due to the low altitude of the AWS. Because the measurement height is only 10 m above the ground, the measured wind speed and direction is vulnerable to errors.

The result from the study says that the AWS data is good enough to be used to find out a spot where the wind speed is relatively higher than other spots. A meteorological mast can

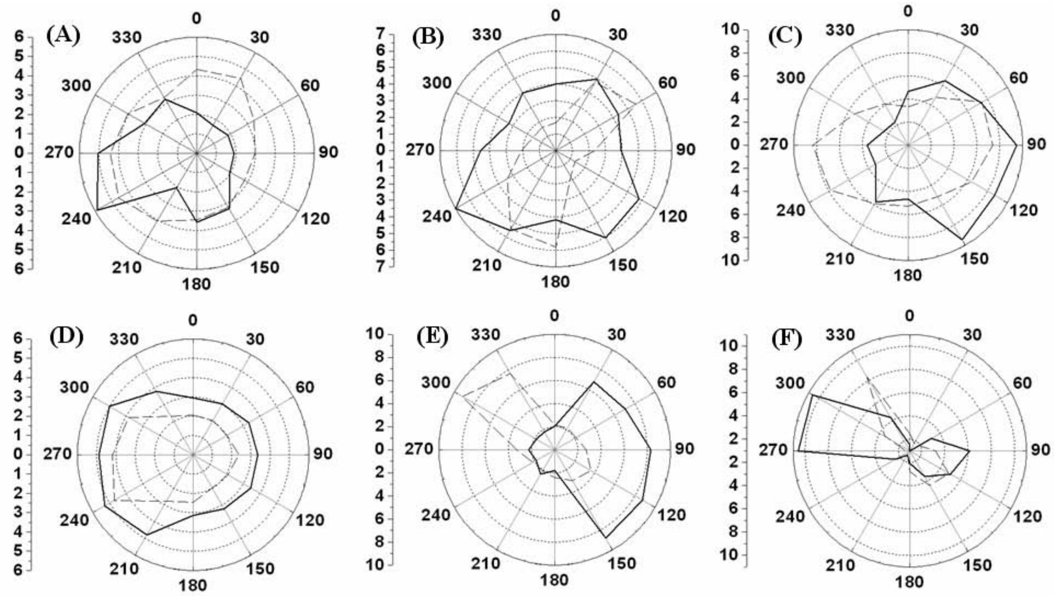


Fig. 4. Prediction of directional mean wind speed. ---: Measurement, —: Prediction.

be installed on that spot to accurately measure the wind speed and direction which will be used for micrositing of wind turbine generators. However, more research needs to be done to find out that if the wind data measured at higher altitudes are used for simulation, the wind rose prediction using the AWS data will be close to that of the measured data.

## Acknowledgment

This work was supported by New & Renewable Energy R&D program (2009T100100621) under the Ministry of Knowledge Economy, Republic of Korea (MKE). This work was also supported by the Human Resources Development of the Korea Institute of Energy Technology Evaluation and Planning(KETEP) grant funded by the Korea government Ministry of Knowledge Economy (No. 2008-N-BN-HM-E-08-0000).

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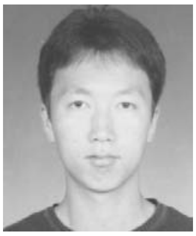

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