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Study on the micro-scale simulation of wind field over complex terrain by RAMS/FLUENT modeling system

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Abstract. A meteorological model, RAMS, and a commercial computational fluid dynamics (CFD) model, FLUENT are combined as a one-way off-line nested modeling system, namely, RAMS/FLUENT system. The system is experimentally applied in the wind simulation over a complex terrain, with which numerical simulations of wind field over Foyeding weather station located in the northwest mountainous area of Beijing metropolis are performed. The results show that the method of combining a meteorological model and a CFD model as a modeling system is reasonable. In RAMS/FLUENT system, more realistic boundary conditions are provided for FLUENT rather than idealized vertical wind profiles, and the finite volume method (FVM) of FLUENT ensures the capability of the modeling system on describing complex terrain in the simulation. Thus, RAMS/FLUENT can provide fine-scale realistic wind data over complex terrains.

Keywords: RAMS/FLUENT system; wind; numerical simulation; complex terrain.

1. Introduction

In the current context of global warming, there exists an urgent need to reduce CO_2 emissions from conventional fossil fuel consumption. The promotion of clean energy, especially wind energy is taken as a way to combat global warming. As is known, the wind energy is proportional to the cube of the wind speed, thus, an important task of wind energy investigation is to map the detailed wind speed distribution over areas of concern, which will help to decide the sites of wind turbine generators. However, in many parts of China, the regions with rich wind energy are usually in mountainous terrain, and the structures of the wind fields over these regions are quite complex. In the regions with mountainous terrain, the numerical simulation is the most important way to map the detailed wind speed distribution and the observed data is more suitable to be used in the numerical model validation for its representativeness is limited in a very small area over

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mountainous terrain.

In fact, the numerical simulation of the wind field over complex terrain has always been an important issue in the field of atmospheric science, and many efforts have been paid on this issue and the studies are related to both engineering application and academic research. Traditionally, mesoscale model is the most important tool in the numerical study on the wind field over complex terrain (Yamada 1992, Enger and Koračin 1995, Venkatesan *et al.* 1997, Tong *et al.* 2005 for example). In most mesoscale models, such as RAMS, WRF and MM5, terrain following coordinates and different levels of smoothness for the terrain data are applied to cope with the complex terrain (Walko and Tremback 2006, Skamarock *et al.* 2008, Dudhia *et al.* 2005). Thus, there is difference between the model terrain and the realistic terrain and almost no mesoscale model will work over an extremely steep terrain.

Fortunately, the application of Computational Fluid Dynamics (CFD) on the wind simulation over complex terrain partially makes up for the shortcomings of the mesoscale models. Compared with mesoscale models, CFD can give wind simulation results with a much higher spatial resolution. Furthermore, the numerical schemes of most CFD tools are based on the finite volume method (FVM), and FVM enhances the capability of CFD on describing realistic terrain for it can be used in grid system fit to the boundary with complex geometry, such as a valley with steep mountains on both sides.

From the point of view of detailed investigation on wind energy in a small area, CFD is a better tool when compared with a mesoscale model for it can cope with steep terrain and can provide simulation results with higher resolution. There have already been some studies on wind simulation over realistic terrain with CFD tools (Montavon 1998, Uchida and Ohya 1999, 2003, Stangroom 2004 for example).

However, when applied on the fine-scale wind simulation over realistic terrain, CFD tools, especially some commercial CFD codes, such as FLUENT and CFX, are vulnerable to criticism for its shortcoming on dealing with the boundary conditions. Mesoscale models can obtain large-scale circulation information from global-scale data, such as NCEP reanalysis data and ECMWF reanalysis data, and pass it to an area of concern through nested-grid techniques. Thus, mesoscale models can ensure that the inlet flow contains the information of the realistic terrain on the upwind direction. Compared with mesoscale models, CFD models usually use simple wind profiles, such as a vertical logarithm wind profile, as the lateral boundary conditions, which can not correctly describe the effects of the realistic terrain on the upwind direction.

In this paper, an approach based on off-line, one-way nesting between a meteorological model, RAMS, and a commercial CFD model, FLUENT, is applied to perform fine-scale wind simulations over realistic complex terrain. RAMS/FLUENT system was initially put forward to simulate the wind and thermal environment within urban surface layer. In the system, RAMS and FLUENT was combined in an off-line way, and the boundary and the initial conditions necessary for driving the FLUENT simulation runs are taken from the simulated results of the RAMS at regular time intervals, which ensures that the boundary conditions for FLUENT simulation are more realistic (Li *et al.* 2007). When applied in the fine-scale simulation of wind field over complex terrain, the most notable advantage of RAMS/FLUENT system is that RAMS can provide realistic boundary conditions containing terrain information on the upwind direction and FLUENT can provide simulation results with a much more higher spatial resolution and can accurately describe complex terrain, even steep terrain, in the simulation.

2. Numerical simulation methods

The domain of numerical simulation is centered around the Foyeding weather station, which is located on the top of a mountain in the north-west part of Beijing. In the Foyeding weather station, the anemometer works on the height of 6.5 meters over the ground. Fig. 1 displays the information on the simulation configuration and the data delivery process.

2.1 Description of RAMS simulation

The RAMS simulation is based on the non-hydrostatic and fully compressible theories, and the governing equations can be found in the documentation of RAMS (Walko and Tremback 1997).

There are totally 4 nested grids used in the RAMS simulation, and all grids have 52×52 cells on the horizontal direction. The horizontal resolutions for the 1st, the 2nd, the 3rd and the 4th grid are 25 km, 5 km, 1 km and 500 m respectively. The 1st grid and the 2nd grid are set for obtaining and passing the large scale background circulation information. The 3rd grid is set for providing the initial and boundary conditions for FLUENT runs. The 4th grid is set for providing data for the inter-comparison between the simulation results from RAMS alone and from RAMS/FLUENT system. Fig. 1(a) displays the area covered by the 2nd and the 3rd grid of the RAMS simulation domain. On the vertical direction, there are totally 35 layers with the grid spacing ranging from 30 to 1000 m, where a stretch ratio of 1:1.15 was employed to adjust the grid spacing.

The RAMS simulation run is initialized and driven by the National Centers for Environmental

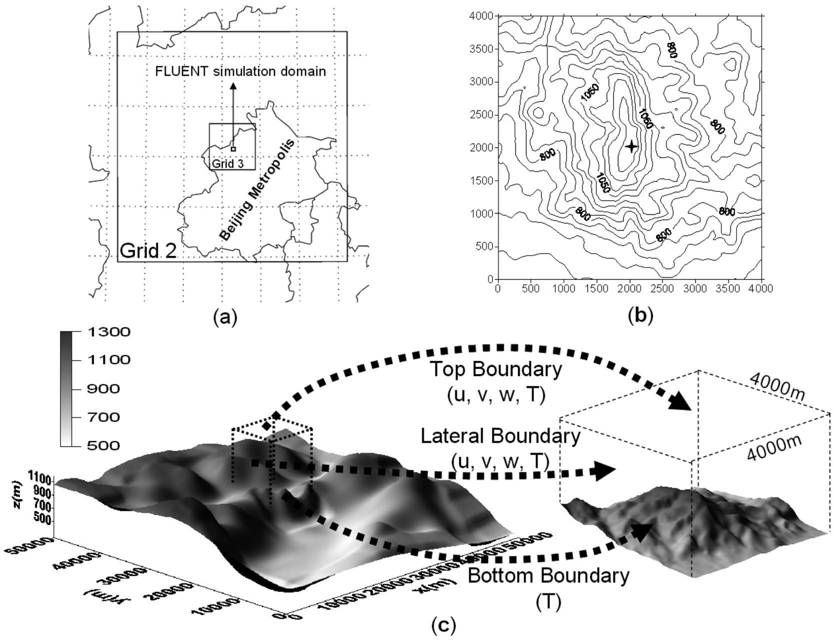

Fig. 1 The sketch map of the numerical simulation configuration: (a) the domains of the 2nd grid and the 3rd grid of RAMS simulation, (b) the terrain of the FLUENT simulation domain, black cross indicates the location of the Foyeding weather station and (c) the data delivery process from the RAMS simulation domain to the boundaries of FLUENT simulation domain at regular time intervals

Prediction (NCEP) reanalysis data with a 1°×1° horizontal resolution. The elevation data and the land use data are from the U. S. Geological Survey (USGS) global database.

2.2 Description of FLUENT simulation

The FLUENT simulation is performed in the RANS (Reynolds averaged Navier-Stokes) framework, the airflow is considered as incompressible and viscous. The Coriolis force is neglected for the characteristic scale of the simulation domain is on the order of kilometers. The governing equations of FLUENT simulation are listed as follows

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\mu}{\rho}\frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j}(\overline{u_i' u_j'}) + f_i \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{2}$$

$$\frac{\partial \bar{T}}{\partial t} + \bar{u}_i \frac{\partial \bar{T}}{\partial x_i} = k\frac{\partial^2 \bar{T}}{\partial x_i^2} \tag{3}$$

where, $\bar{u}_i$ is mean velocity, u_i' is turbulent variations, ρ is air density, f_i is buoyancy, $\bar{T}$ is mean temperature. The turbulence closure model adopted in the FLUENT simulation is realizable k-ε model, which is the best one among all k-ε models integrated in FLUENT in the light of the authors' previous study (Li *et al.* 2004, 2006). In order to describe the thermal process, the Boussinesq approximation is used in the FLUENT simulation.

The location of the FLUENT simulation domain is shown in Fig. 1(a), which is of a size of 4 km×4 km on the horizontal direction, and the terrain with a horizontal resolution of 100 m is quite complex in the domain, just as shown in Fig. 1(b). The top of the FLUENT simulation domain reaches a height of about 2600 m. As shown in Fig. 2, the whole FLUENT simulation domain is discretized with body-fitted hexahedral grid system. There are 80×80 cells on the horizontal direction, which means that the horizontal resolution is around 50 m. On the vertical direction, there are totally 40 layers, and a ratio of 1:1.02 is used to adjust the grid spacing. In the FLUENT simulation domain, there are the same number of vertical layers in each column above the bottom boundary, whereas the depth of each column is different, for the top height of the simulation domain is fixed and the elevation of the bottom varies from cell to cell. Thus, the vertical grid spaces are not uniform on the horizontal direction and the grid spaces range from 7.4 m to 10.6 m in the lowest layer.

2.3 The combination between RAMS and FLUENT

RAMS and FLUENT are coupled in an off-line way. As shown in Fig. 1(c), the simulated wind and temperature data of the 3rd grid in the cells near the lateral, the bottom and the top boundaries of the FLUENT simulation domain are extracted from RAMS output files, which are output during RAMS simulation every 6 hours. The extracted data and the corresponding Cartesian coordinate parameters (x, y and z values) are deposited in Boundary Profile (BP) files with a format predefined in FLUENT. These files can be read through the BP interface of FLUENT and the data is interpolated on all 6 boundaries of the simulation domain.

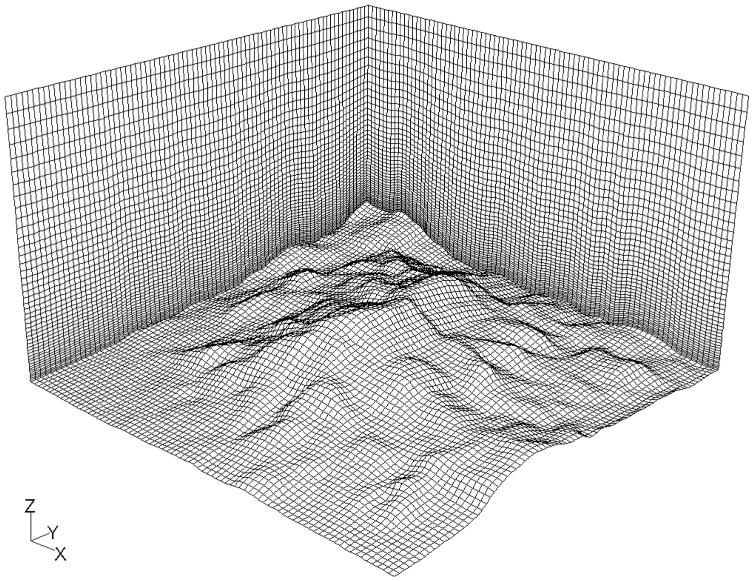

Fig. 2 The body-fitted hexahedral grid system used in the FLUENT simulation

When driving a FLUENT simulation run, the lateral boundaries and the top boundary are set as velocity-inlet boundaries and the velocity and the temperature data from the RAMS output are interpolated on the lateral boundaries and the top boundary. The bottom boundary is set as non-slip wall boundary with a roughness length of 0.2 m (the vegetation type in the FLUENT simulation domain is deciduous shrub with sparse trees) and surface temperature from the RAMS output are interpolated on the bottom boundary. The boundary conditions setting in the simulation can provide a strong forcing for the FLUENT integration.

3. Simulation results and analysis

3.1 Time series

The simulation starts at 00 UTC on 17 January 2005 and ends at 00 UTC on 20 January 2005, during which time the measured wind direction was principally northwest and the wind speed was quite high. The first 12 hours is treated as the spin-up period, thus the analysis on the simulation results starts at 12 UTC on 17 January 2005.

The time series of the simulated wind speed and wind direction data from the 4th grid of the RAMS simulation (hereafter called as the RAMS simulation) and from the RAMS/FLUENT simulation are compared in Fig. 3, which are interpolated at the point where the anemometer of the Foyeding weather station is located. From Fig. 3(a), it can be found that the wind speed data from the RAMS/FLUENT simulation are closer to the observed data than those from the RAMS simulation. The root mean square errors (RMSEs) of the wind speed are 4.06 and 1.98 for the RAMS simulation and the RAMS/FLUENT simulation, respectively. From Fig. 3(b), it can be seen that the wind direction from the RAMS/FLUENT simulation are also closer to the observed data

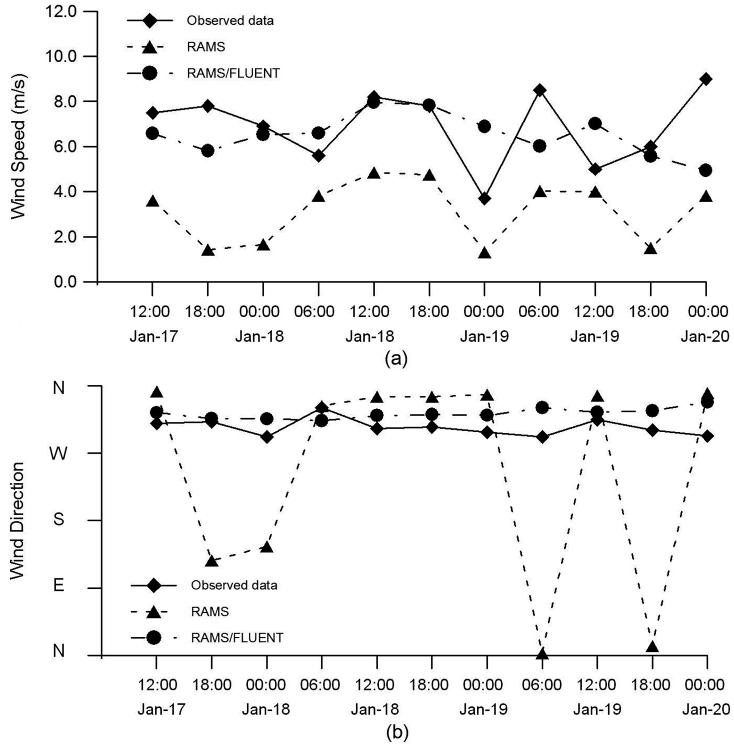

Fig. 3 The time series of the wind speed and the wind direction: (a) wind speed and (b) wind direction

than those from the RAMS simulation. In the RAMS/FLUENT simulation, the wind directions keep as NW during the period, which are accordant to the observed data. However, there are quite obvious differences between the wind direction data from the RAMS simulation and the observed data at 18 UTC on 17 January and 00 UTC on 18 January. The RMSEs of the wind direction in degree (^{o}) are 84.22 and 24.40 for the RAMS simulation and the RAMS/FLUENT simulation, respectively. However, it should be pointed out that the differences between the observed wind directions and the simulated wind directions from RAMS simulation at 06 UTC and 18 UTC on 19 January are not as drastic as are shown in Fig. 3(b), for both the observed and the simulated wind directions from RAMS are actually around the N direction at the two times. Furthermore, when calculating the RMSEs of the wind directions, a value of 360 is added for the simulated wind directions from RAMS at 06 UTC and 18 UTC on 19 January to avoid incorrectly amplified RMSEs.

Based on the analysis on the time series of the wind speed and the wind direction, it can be seen that RAMS/FLUENT system can provide relatively more accurate simulation results when compared with RAMS alone.

3.2 Wind field

For better illustrating the difference between the two simulation methods, a comparison between the wind speed distribution at the height of 10 m from the RAMS/FLUENT simulation and the RAMS simulation at 06 UTC on 18 January 2005 are shown in Fig. 4, in which the wind speed data are interpolated into grids with a horizontal resolution of 40 m. It can be found in Fig. 4 that

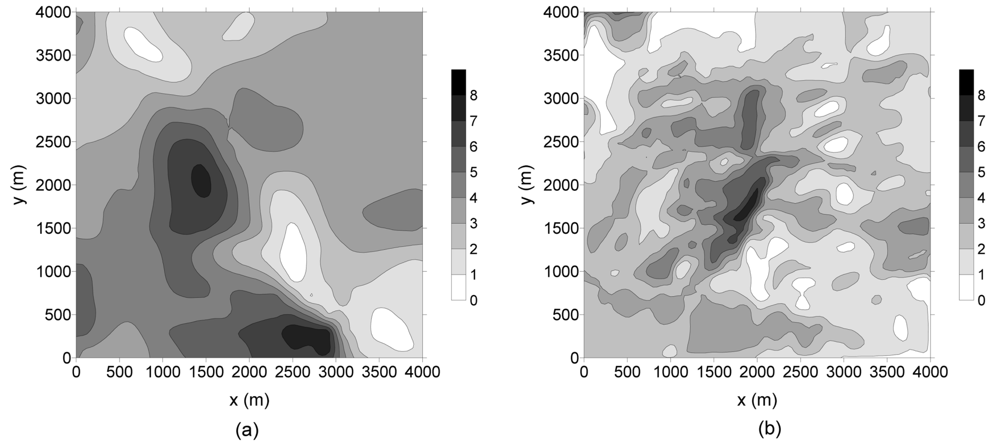

Fig. 4 The simulated wind speed data at the height of 10 m at 06 UTC on 18 January 2005: (a) RAMS simulation and (b) RAMS/FLUENT simulation

the horizontal wind speed distribution from the RAMS/FLUENT simulation shows a more heterogeneous manner than that from the RAMS simulation. In the RAMS simulation, there are two regions with wind speed over 8 m/s, one is northwest to the Foyeding weather station and the other is near the southern lateral boundary of the simulation domain, and the wind speed over the Foyeding weather station is around 4 m/s. However, in the RAMS/FLUENT simulation, the region with wind speed over 8 m/s is just over the Foyeding weather station, which is accordant to the observed data.

Fig. 5 illustrates the simulated wind fields at the height of 10 m, which are also interpolated into grids with a horizontal resolution of 40 m. From Fig. 5, it can be seen that the simulated wind fields from the RAMS simulation and the RAMS/FLUENT simulation are similar on the whole at 06 UTC on 18 January, for the prevailing wind direction are northwest in both simulations. However, the details of the wind fields from the two simulations are quite different. Especially, in Fig. 5(a), there is an obvious convergence line in the northwest part of the RAMS simulation domain, and on

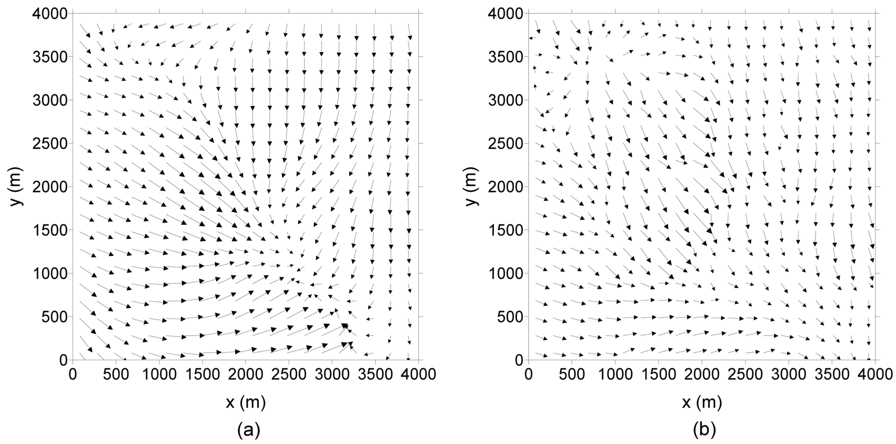

Fig. 5 The simulated wind fields at the height of 10 m at 06 UTC on 18 January 2005: (a) RAMS simulation and (b) RAMS/FLUENT simulation

the contrary, in the same part of the RAMS/FLUENT simulation domain, the wind field is divergent on the whole. Furthermore, it can be seen that the wind field from the RAMS/FLUENT simulation shows a more heterogeneous manner, and the wind field from the RAMS simulation is relatively smooth.

From Fig. 5, it is difficult to determine which wind field is closer to the realistic one over the region for there is only one weather station in the simulation domain. However, RAMS/FLUENT system does provide a more complex and heterogeneous wind field, which should be more realistic over a highly complex terrain than a smooth one.

3.3 Model terrain

In Fig. 6, the model terrains are extracted from the RAMS simulation and the RAMS/FLUENT simulations respectively and interpolated into grids with a horizontal resolution of 40 m. From Fig. 6, it can be concluded that the difference between the wind fields from the RAMS simulation and the RAMS/FLUENT simulation can be at least partially due to the model terrains. From Fig. 4(a), it can be found that the model terrain in RAMS simulation is quite smooth, for it is interpolated from the USGS global database, which is of a horizontal resolution of about 1 km, and has been smoothed in the preprocess of RAMS simulation in order to get a steady integration. On the contrary, the model terrain in RAMS/FLUENT simulation is much more complex, for it is based on a database of a horizontal resolution of 100 m and has not been smoothed in the simulation. Thus, the simulated wind fields are quite different in the two simulations.

3.4 Analysis

RAMS is mainly used as a mesoscale meteorological model in many studies, though it is put forward as a comprehensive model. When directly applied in the fine-scale wind simulation, the model terrain of RAMS should be smoothed in the preprocesses of the simulation in order to get steady integration, which will lead to the failure on describing the details of the wind field over complex terrain.

On the other hand, as a CFD model, FLUENT is based on the FVM method and there is no smoothness for its model terrain, which ensures its capability on describing the details of wind field

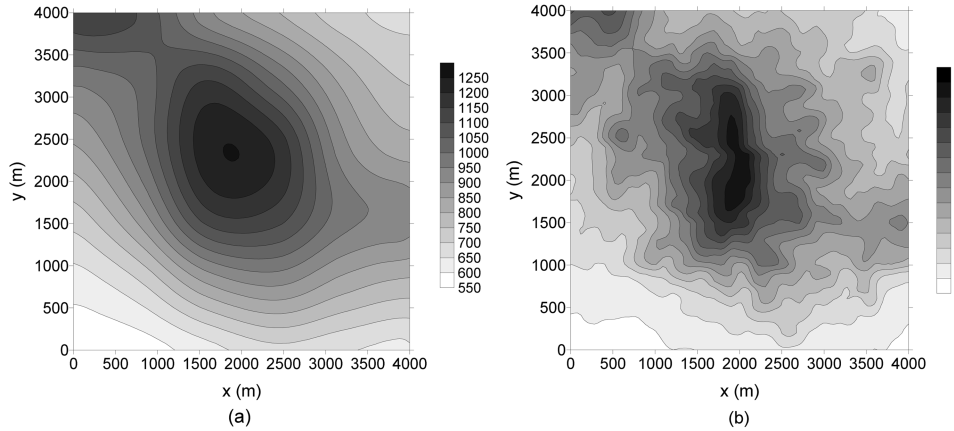

Fig. 6 The terrain read in the simulation: (a) RAMS simulation and (b) RAMS/FLUENT simulation

over realistic complex terrain. Furthermore, though FLUENT is a sealed commercial model, it provides rich interface modules for acquiring external data, such as BP module and UDF (User Defined Function) module, which ensures its capability on linking with other models.

In RAMS/FLUENT system, more realistic boundary conditions are extracted from RAMS and delivered to FLUENT, and the FVM method of FLUENT ensure the capability of the system on describing realistic complex terrain. Thus, RAMS/FLUENT system can provide more realistic wind data over complex terrain than any single model of RAMS and FLUENT.

4. Conclusions

In this paper, a meteorological model, RAMS, and a commercial CFD model, FLUENT, are combined as a one-way off-line nested modeling system, which is called as RAMS/FLUENT system, and are experimentally applied in the wind simulation over the Foyeding weather station located in the northwest mountainous area of Beijing metropolis. The simulated results from the RAMS/FLUENT simulation are compared with the results from the RAMS simulation and the observed data, and some conclusions can be drawn through the comparison:

(a) RAMS/FLUENT system can provide reasonable wind field over a complex terrain. The time series data from the RAMS/FLUENT simulation is closer than the observed data than those from the RAMS simulation.

(b) The wind filed from the RAMS/FLUENT simulation is relatively heterogeneous, and the wind field from the RAMS simulation is relatively smooth. The difference between the wind field from the RAMS simulation and that from the RAMS/FLUENT simulation can be at least partially due to the difference between the model terrains from the two simulations.

(c) The method of combining a mesoscale model and a CFD model as a modeling system is reasonable, for it provides a way to take advantage of the merits of both kinds of models. In RAMS/FLUENT system, more realistic boundary conditions are provided for FLUENT rather than idealized logarithmic or exponential vertical wind profile, and the FVM method of FLUENT ensures its capability on describing complex terrain. Thus, both the boundary conditions and the model terrain for an area of concern are more realistic in the system. In the future, it can be expected that RAMS/FLUENT system will be applied in detailed investigations on wind energy over mountainous regions after further validation studies.

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