Yale 耶鲁大学-南京信息工程大学大气环境中心

Yale-NUIST Center on Atmospheric Environment

Master's thesis (wind energy)

Fine numerical simulation of wind field in complex atmospheric terrain with atmospheric boundary layer based on CFD downscaling

Reporter：Zhang Jiarong

Tutor：Wang Yongwei

/Cheng Xueling

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Research meaning

The true underlying surface is characterized by complex topographic relief. Different terrain conditions cause significant differences in the near surface atmospheric flow field. Accurately predicting the structure of the flow field near the complex terrain is of guiding significance for the improvement of the numerical weather forecast, the prediction of meteorological disasters and the assessment of the wind resources.

At present, the methods of obtaining wind field distribution in complex terrain include field measurement, wind tunnel experiment and numerical simulation. The field measurement requires a large number of equipment, and the wind tunnel experiment takes into account the cost, the cycle and the test accuracy, which is not suitable for obtaining the flow field under the complex terrain condition. In this case, the method of numerical simulation is particularly important.

Research status and development trend at home and abroad

A large number of studies have been done on the numerical simulation of wind field structure in complex terrain at home and abroad. It can be divided into two categories: Diagnostic Models and Prognostic Models.

However, in order to satisfy the finely numerical simulation of the complex terrain wind field, it is difficult to achieve the precision demand simply by Prognostic Models. Even if Prognostic Models of the fine simulation can be realized, it takes a lot of time for the regional simulation. Therefore, it is necessary to realize **the finely numerical simulation** by the method of dynamic downscaling. The three-dimensional flow field is calculated by combining Prognostic Models with Diagnostic Models.

In recent years, with the enhancement of computer ability, more and more Computational Fluid Dynamics (CFD) models used to calculate the fine flow field of aerodynamics have been applied in the field of meteorology, especially in the study of urban micro scale wind field and pollution diffusion.

Scientific problems

In the process of combining the CFD model with the mesoscale forecasting model, there are not only the technical problems of constructing high precision grid and mode coupling, but also the modification of the schema parameterization scheme and the scientific problems of increasing the necessary physical models.

FLUENT is an internationally famous CFD mode, which integrates very rich parametric schemes and physical models. In the numerical calculation method, FLUENT uses the finite volume method (Finite Volume Method, FVM) as the core method, which can be used to solve the numerical solution of unstructured grid system. The preprocessor GAMBIT of FLUENT has a fairly strong modeling function, and it can cope with various complex geometries in the solution domain. At the same time, FLUENT also provides a custom function interface (UDF) for adding the necessary physical models and linking external data. These characteristics of FLUENT make it possible to simulate wind fields on complex terrain.

Scientific questions 1:

The turbulence model of FLUENT has both traditional RANS based turbulence closure schemes and various sub grid (sub-grid) models based on LES mode. Studies have shown that although the numerical simulation method based on the RANS equation can accurately calculate the mean value of the wind field, the fluctuation value of turbulence is not accurate. Therefore, it is more inclined to use the LES model to calculate the flow field of complex terrain. The small scale turbulence after subgrid filtration in the LES mode is more isotropic, so the calculation of turbulence closure scheme is more reasonable and accurate.

Scientific question 2:

The atmosphere is a layer of stratified fluid, and the vertical movement of air is closely related to the different types of atmospheric stratification because of the obvious change in the atmospheric temperature, density and water vapor in the vertical direction. FLUENT can increase the physical model of temperature stratification through the user defined function (UDF) interface to analyze the buoyancy effect on the atmospheric flow.

The purpose, content and method of this paper

The Poyang Lake area of Jiangxi province is mainly mountainous and hilly. This paper takes the region near jiishan tower in Poyang Lake area of Jiangxi Province as the simulation object, and according to the different selection of the Fluent model turbulence scheme in the simulation scheme and the introduction of the external physical model, the simulation object is simulated respectively, the purpose is to improve the existing Fluent model, develop the WRF coupled Fluent mode simulation method to simulate the near surface flow field more accurately under complex terrain conditions.

The specific contents are as follows: using WRF and Fluent coupling calculation, using high precision grid, according to the use of different turbulence parameterization schemes (realizable k-ε model and large eddy simulation (LES) model), two examples are designed respectively. The latter considers the influence of temperature layer on the atmospheric flow, and is attached to simulated the wind field near the complex boundary of the atmospheric boundary layer of Jishan wind tower in the Poyang Lake area finely. The simulation results of these two examples will be compared and evaluated.

Model introduction

WRF

Weather Research and Forecasting (WRF) It is a new generation of high resolution mesoscale weather forecast research system developed by the National Center for Atmospheric Research (NCAR) and the National Environmental Prediction Center (NCEP) of the United States. This article uses the WRF3.7 version, whose main components are shown in Figure 1.

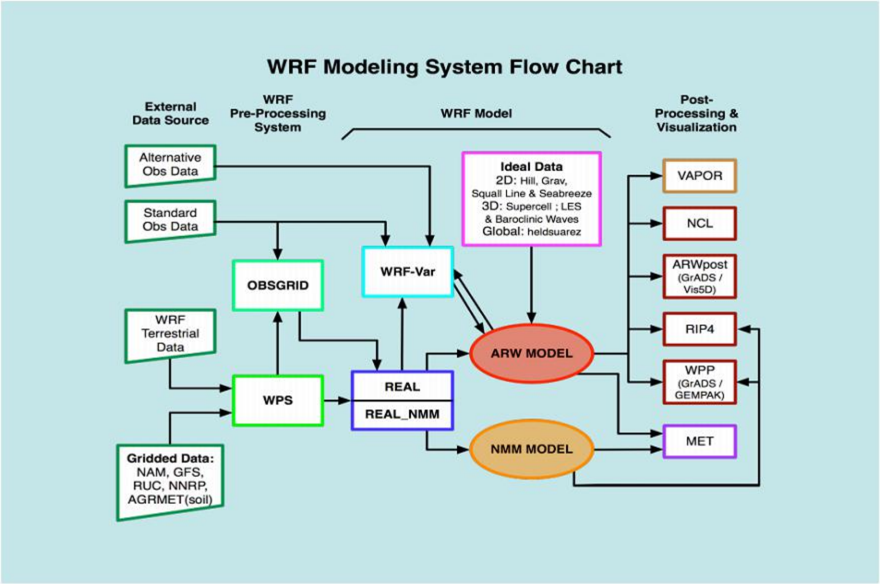


Figure 1 WRF module flow chart

Fluent

The all governing equations of fluids are Navier-Stokes equations. When calculating the mesoscale wind field, Fluent often assumes that the air motion is a three-dimensional incompressible steady flow, neglecting the influence of geostrophic force.

The Reynolds averaged Navier-Stokes equation can be rewritten as follows:

$$\frac{\partial}{\partial x_i}(\rho \overline{u_i}) = 0 \qquad (1)$$

$$\frac{\partial(\rho \overline{u_i u_j})}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}[\mu(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial \overline{u_l}}{\partial x_l})] + \frac{\partial(-\rho \overline{u_i' u_j'})}{\partial x_j} + \overline{\rho g} \qquad (2)$$

The equation (2) is more than one unknown term, the Reynolds stress tensor, for equation (3), represents the correlation of the velocity fluctuation, and needs to be parameterized to close the RANS equation.

$$-\rho \overline{u_i' u_j'} \qquad (3)$$

Fluent integrates a variety of turbulent Reynolds stress parameterization schemes, including k- ω scheme, k-ε scheme, Reynolds stress transport model and large eddy model (LES). Among them, the k-ε solution is the most mature way to match the computation accuracy with the computing resources, and ensure reliable results and stability. It has been shown that in the three k-ε schemes (standard k-ε scheme, RNG k-ε scheme and realizable k-ε scheme), the realizable k-ε scheme has the best effect on simulating the atmospheric motion of complex terrain.

LES can give the best parameterization results, but it consumes more computing resources.

This paper mainly studies the realizable k-ε and LES schemes. The detailed introduction is in the 2.2 section of the article.

The route of WRF drives Fluent

WRF part

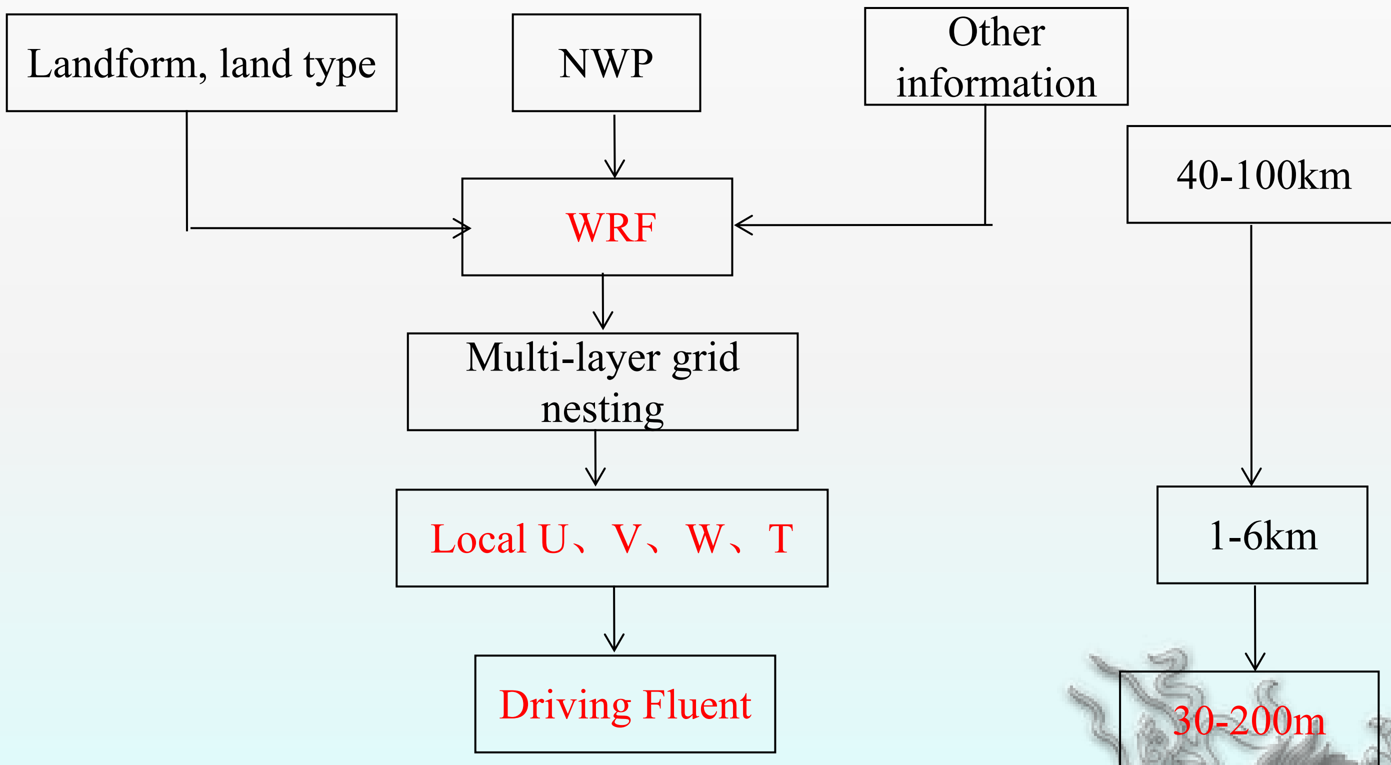


Figure 2 WRF simulated local wind field driven Fluent

Fluent part

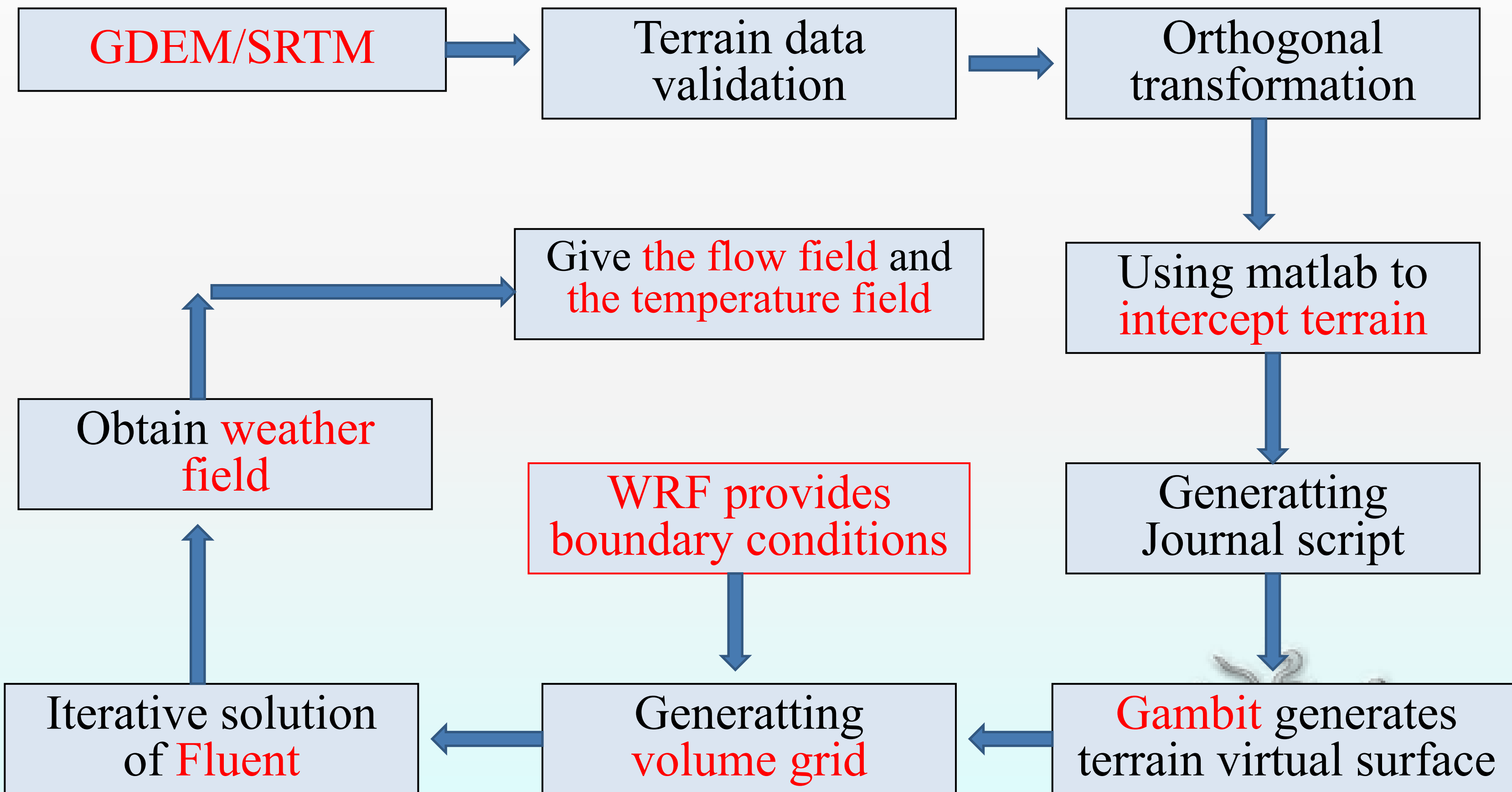


Fig. 3 Fluent accepts the WRF boundary condition to solve the more subtle wind field

Simulation area and simulation setting

The simulation area is shown in Figure 4, including most parts of northern Poyang Lake, Jiangxi. The Poyang Lake plain is a lacustrine plain formed by alluvial rivers such as Gan, Fu, Xin, Rao, Xiu, and so on for the Yangtze River and Poyang Lake river system. Jiangxi belongs to the subtropical monsoon climate. The southerly winds prevail in summer, and are occasionally affected by typhoons. The period is northerly and the northerly winds prevail in winter.

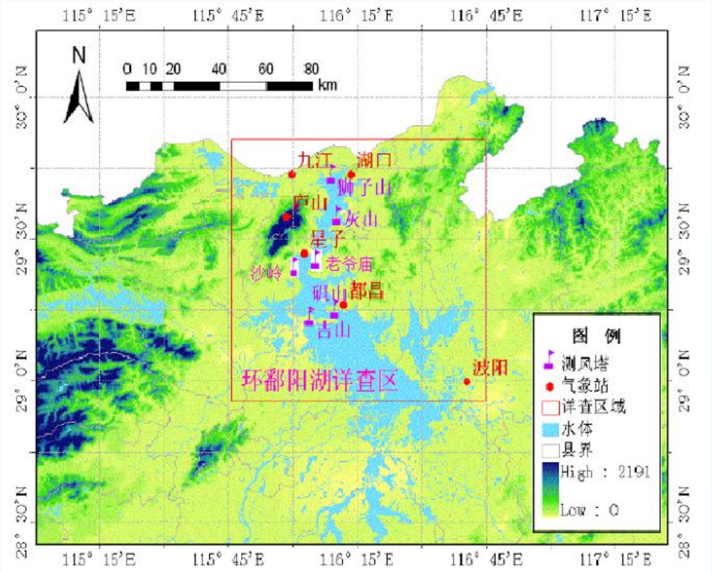


Figure 4 the location and simulation area of the observation tower

Observation data are introduced.

The Jishan measuring tower is located on the West Bank of Poyang Lake. Please refer to table 1 for detailed instructions. The data obtained from Jishan station are observed during 2010-12 to 2011-03 (wind speed and wind direction).

Table 1 the general situation of jiishan wind measurement station

The sequence number of the wind tower	**City and county**	**Name of the observation tower**	**longitude(°)**	**Latitude(°)**
14004	Yongxiu County	Jishan	116.07152	29.23060
Altitude（m）	**Topographic features**	**Area range**	**Height of the wind tower**	**Levels of measurements**
89	Hilly of shallow mountains	17.5km^2	70m	4

WRF settings

The location of the pattern simulation area is shown in Figure 5. Three layer grid bidirectional nesting is applied to the simulation area. The third layer (domain3) spacing is 6km and the lattice number is 82 * 64, which covers the Poyang Lake area. Topographic data are based on MODIS grid data, and the background data of the background field are NCEP reanalysis grid data.

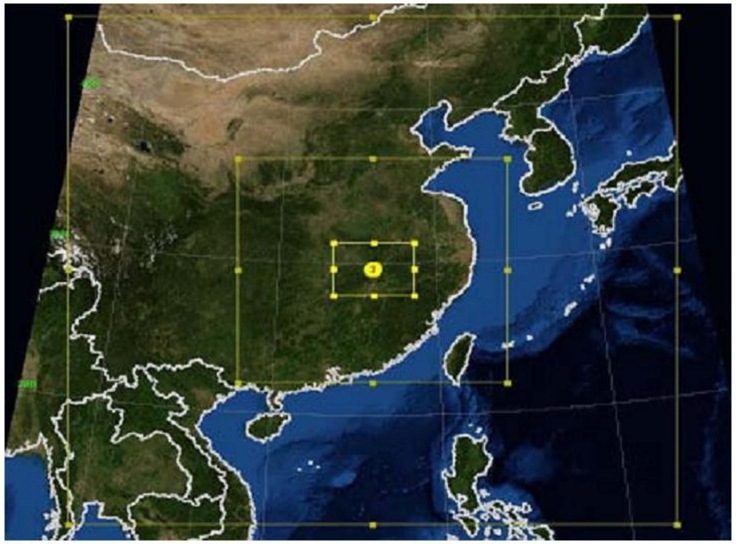


图5 鄱阳湖WRF模拟网格区域

Fluent grid partition and setting

According to the Fluent part of the Fluent process driven by the above WRF, the terrain in the 3.6km*3.6 km area near jiishan station is intercepted, and the virtual surface of the terrain is generated, and the structure type grid is obtained. Fig. 6 (a) represents the intercepted terrain near Mount Jishan, Poyang Lake.

The horizontal resolution of the body grid (scheme 1) is 50 *50m, the height of the first layer network in the vertical direction is 1m, the 1m outer grid is gradually pulled up and the height of the top layer grid is 1km. The grid of scheme 2 is encrypted in the center 1.2km * 1.2km area, the resolution is 7.5m * 7.5m, and the vertical grid design is the same as the scheme 1. For scheme 1, the total number of grids is 84 * 84 * 50, and the scheme 2 is 220 * 220 * 50.

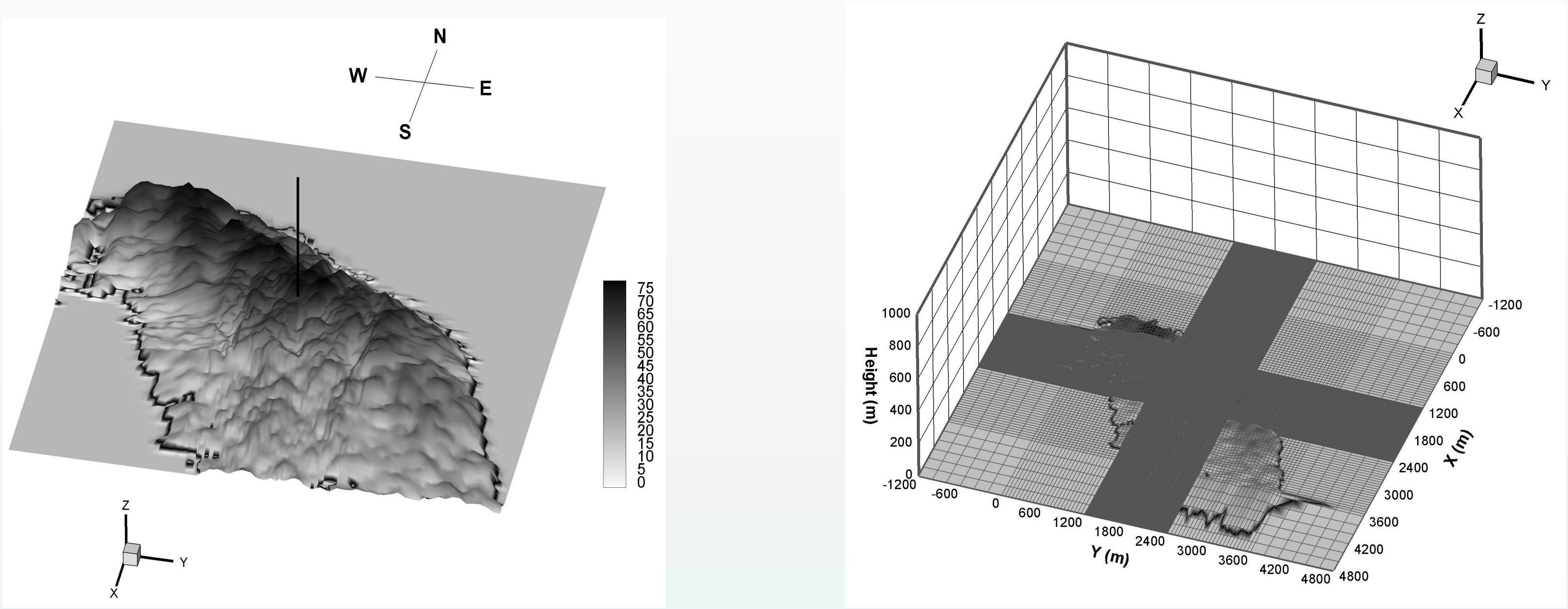


Fig. 6 terrain area (a) terrain capture, (b) grid (example 2)

Fluent boundary condition

According to WRF's innermost grid output, the wind speed, wind direction and air temperature are determined by interpolation, and updated every 1hour. The boundary conditions for scheme 1 are wind speed and wind speed. The boundary conditions used in scheme 2 are wind speed and air temperature.

Example design

The design examples include two examples of WRF coupled Fluent models (Examples 1, 2) and WRF direct simulation of three schemes, of which 1 and 2 are coupled to Fluent after the direct simulation of WRF. In the selection of Fluent turbulence model, the schemee 1 selects the realizable k-ε model, and the example 2 chooses the large eddy model. In addition, the momentum equation of the LES turbulence scheme in Fluent itself has no buoyancy. In scheme 2, a buoyancy term $\frac{\overline{\theta}-\overline{\theta_0}}{\overline{\theta_0}} g\delta_{i3}$ is added to the right side of the momentum equation (12) through the UDF interface of Fluent, and the physical model of the temperature layer is introduced to analyze the effect of the buoyancy effect on the atmospheric flow. The details of these three examples are shown in Table 2.

Table 2. The details of three examples

Scheme	WRF	Scheme1	Scheme2
Whether or not to coupling Fluent	No	Yes	Yes
Whether or not a temperature stratification model is leaded into	—	No	Yes
Types of turbulence models in Fluent	—	realizable k-ε	LES

Results and analysis

The following is the simulation of a large wind process (the national cold wave process) in the 2010.12.13 08h-2010.12.16 08h section. The quantitative analysis of the 70m height wind speed of WRF direct simulation and scheme 1 and 2 simulated Jiangxi Jiishan station observation station is compared with the measured data.

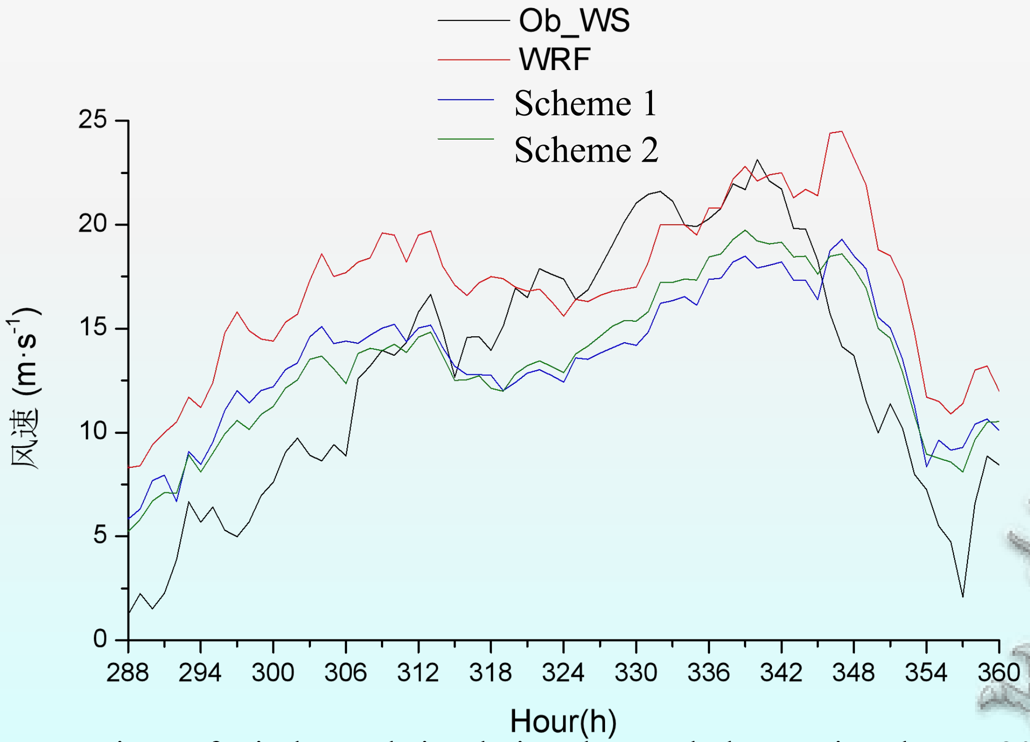


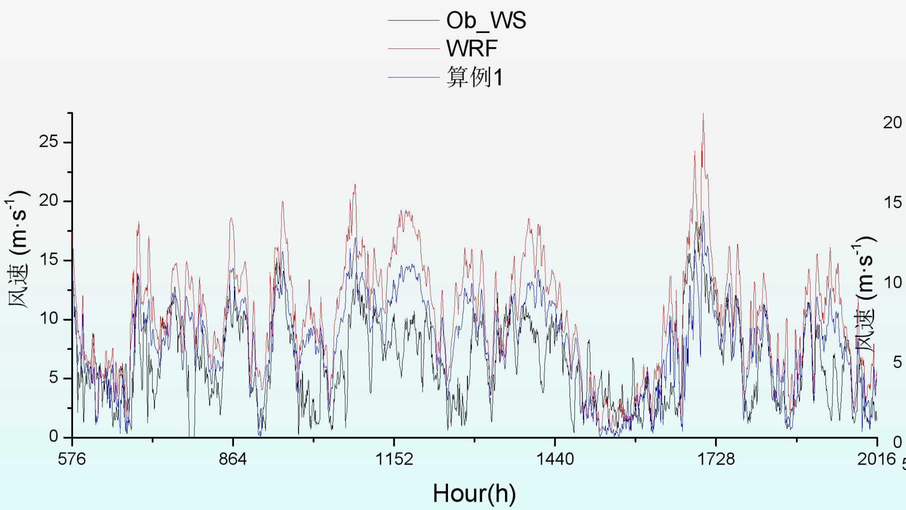
Fig. 11 comparison of wind speed simulation data and observation data at 2010.12.13 08h-2010.12.16 08h gishan 70m height

Table 3 evaluation indexes for the wind speed simulation results at 2010.12.13 08h-2010.12.16 08h Jishan 70m height

	WRF	**Scheme 1**	**Scheme1 2**
BIAS	4.602	3.755	3.104
RMSE	3.956	4.133	3.423
R	0.785	0.791	0.883

The overall simulation time is from 2010-12 to 2011-03, and the simulation results of WRF, 1 and 2 are compared with observed data respectively.

The simulation results of 70m high wind speed at jiishan station are compared with the observed data (for the purpose of showing clearly, the two maps show 1440 hours' comparison results).



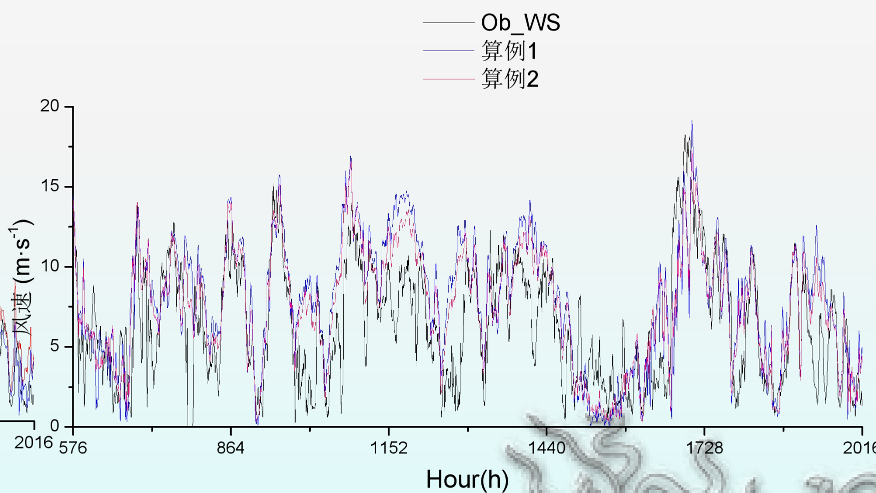
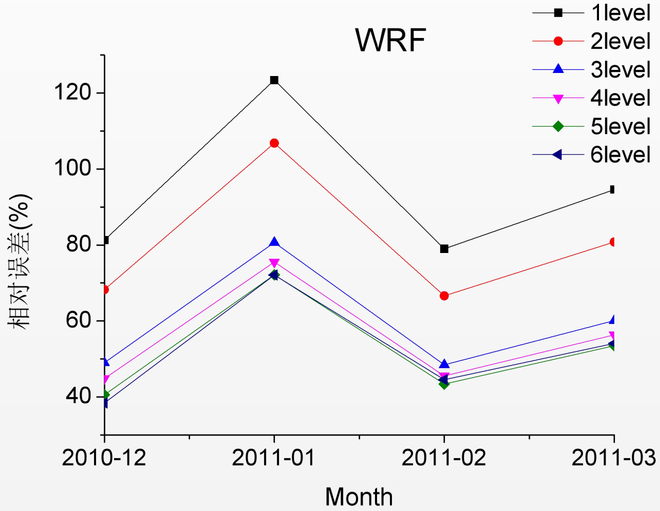


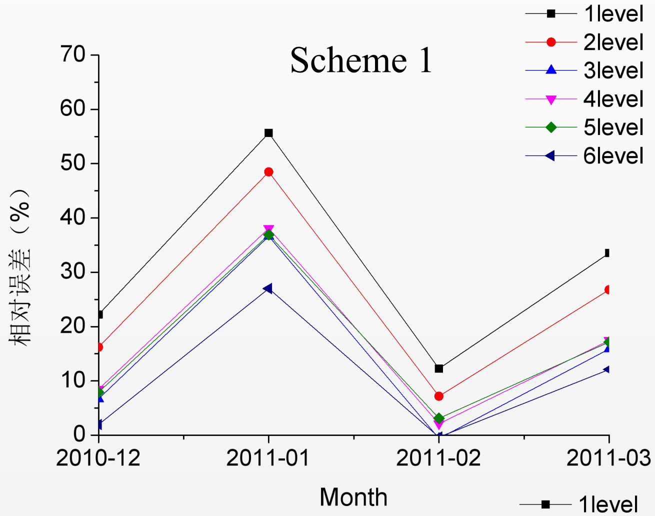
Fig. 12 comparison of simulated results and observed data of high wind speed WRF, scheme 1 and scheme 2 at 70m of Jishan.

Table 4 indicators for the overall simulation results of the 4 month wind speed at 70m height of Jishan

	WRF	Scheme 1	Scheme1 2
BIAS	3.963	2.727	2.224
RMSE	3.708	3.351	2.752
R	0.710	0.682	0.778

Comparison of simulation results of monthly mean wind speed at different heights (4m, 10m, 30m, 50m, 70m and 100m) at jiishan station and observation data





The scheme 1 relative error of the 6 levels height and 4 months mean wind speed are 30.9%, 24.7%, 14.7%, 16.5%, 16.3% and 10.2%, respectively. The relative errors of the scheme 2 are 26.9%, 22.5%, 12.8%, 12.3%, and 9.3%, respectively.

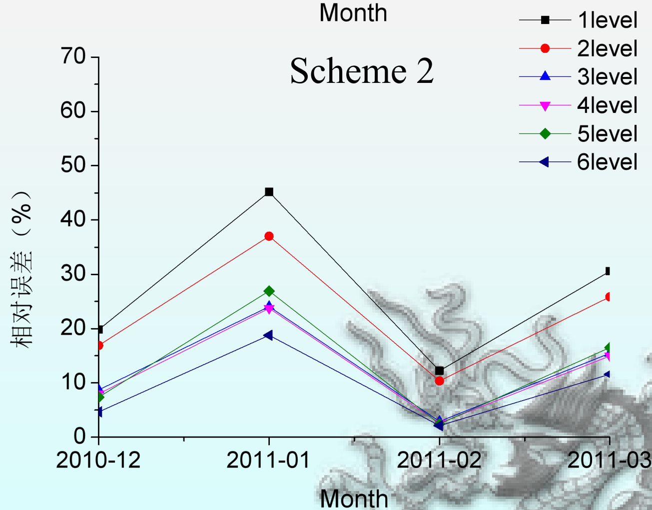


Fig. 13 error of wind speed simulation and observation in three schemes of Jishan station

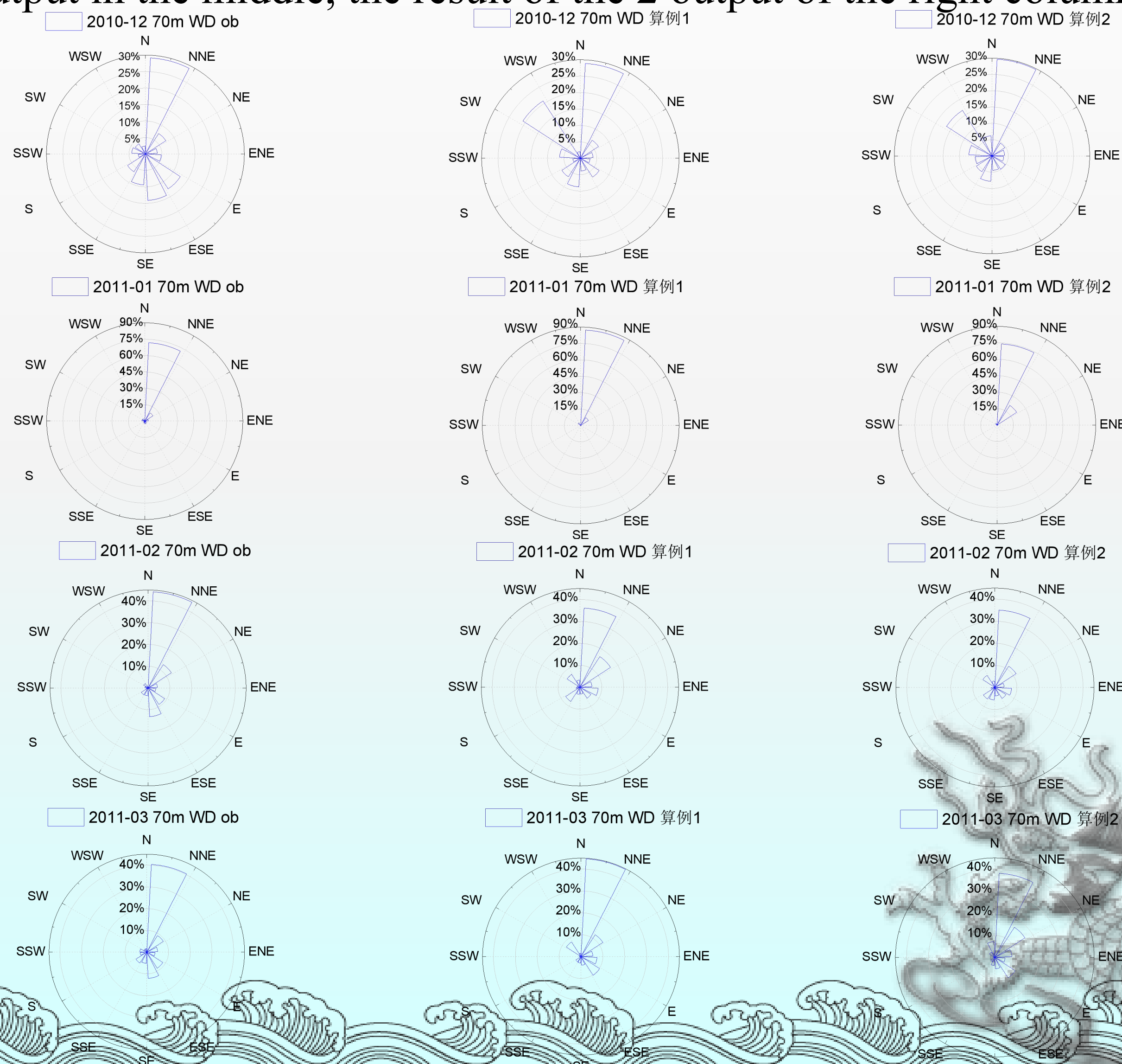
The comparison of the simulation results of the 4 month wind direction to the rose map (70m) is compared with the observed data (the result of the observation on the left column, the result of the 1 output in the middle, the result of the 2 output of the right column example).

2010-12

2011-01

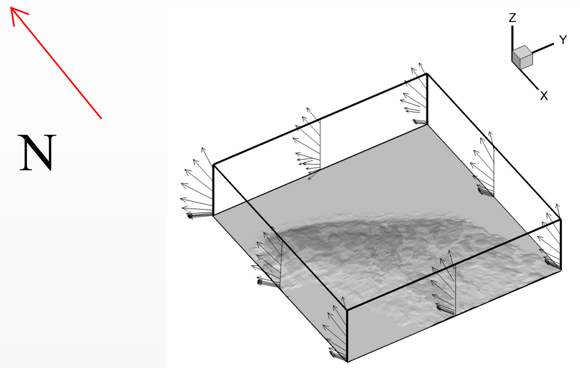
2011-02

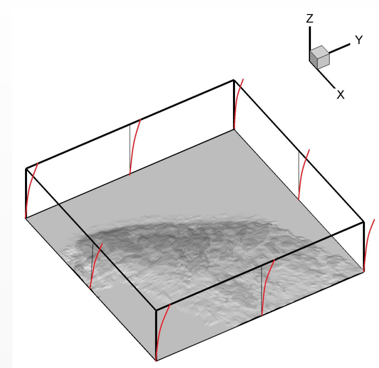
2011-03



Temporal and spatial characteristics of flow field and atmospheric temperature field at typical time

On the basis of the comparison and evaluation of the observation data, by further studying the spatial and temporal characteristics of the flow field and the atmospheric temperature field near the jiishan station, we evaluate the simulation results of schemes 1 and 2 schemes. The evolution characteristics of flow field and temperature field of 1 hours averaged were analyzed by selecting two typical days of 2011-03-06 at 14 and 24 o'clock.

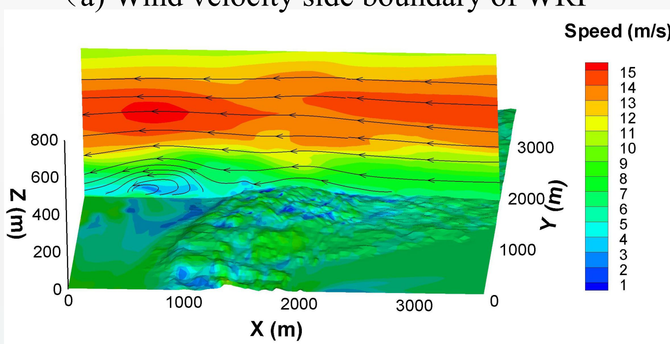




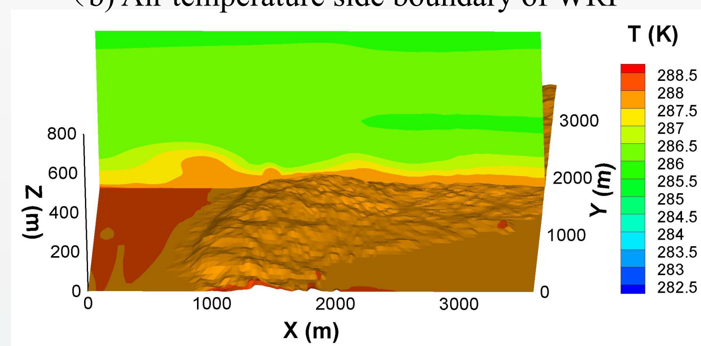
（a) Wind velocity side boundary of WRF

（b) Air temperature side boundary of WRF

scheme2

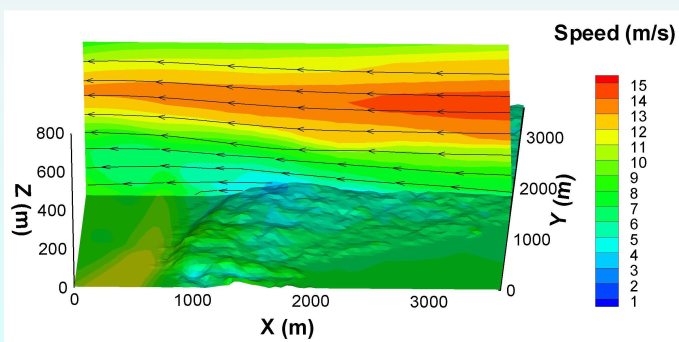


（c)



（d)

scheme1

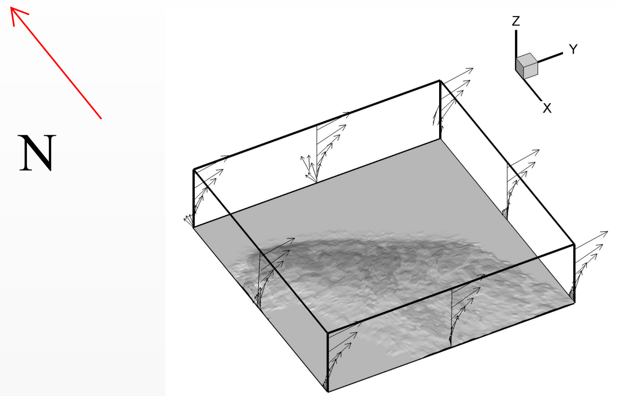


（e)

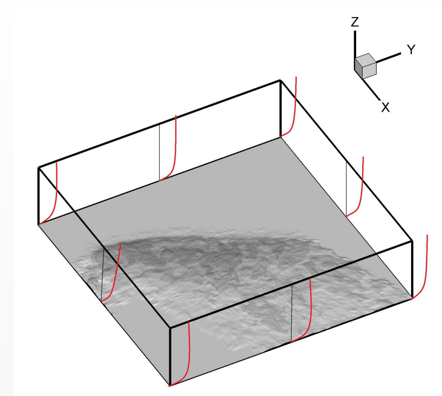
Wind field

Air temperature field

Fig. 14 Side boundary conditions and simulation results of scheme 2 (c) (d), simulation results of scheme 1 (E)at 14 p.m.

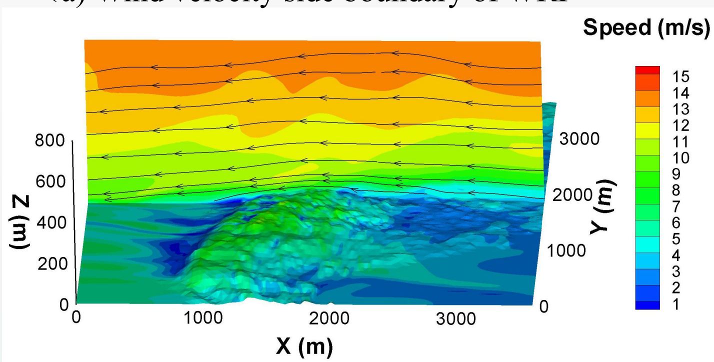


（a) Wind velocity side boundary of WRF

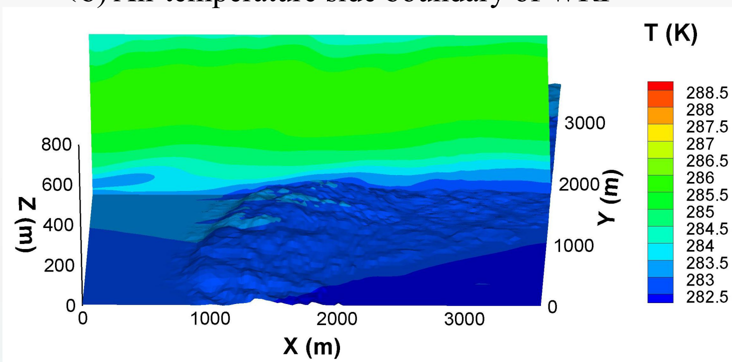


（b) Air temperature side boundary of WRF

scheme2

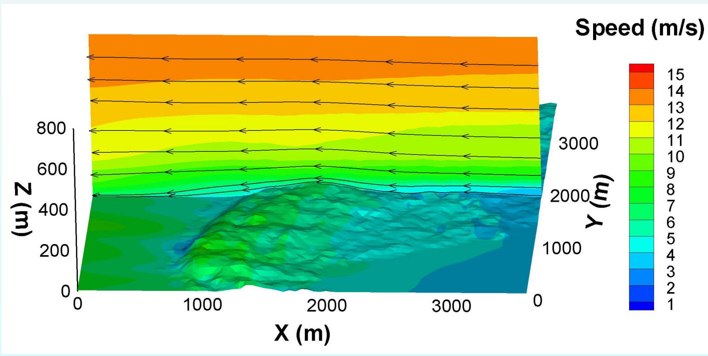


(c)



(d)

scheme1



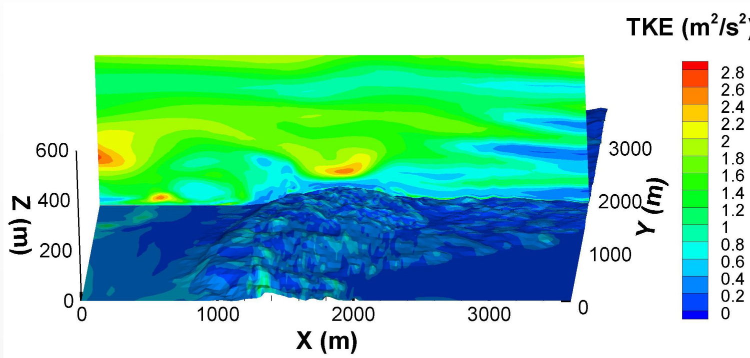
(e)

Wind field

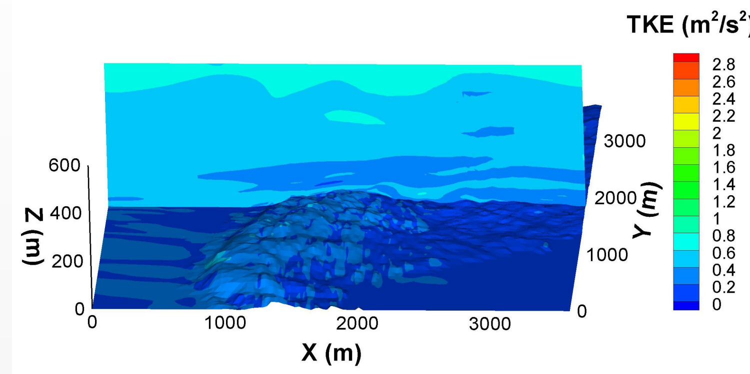
Air temperature field

Fig. 15 Side boundary conditions and simulation results of scheme 2 (c) (d), simulation results of scheme 1 (E)at 24 p.m.

scheme2

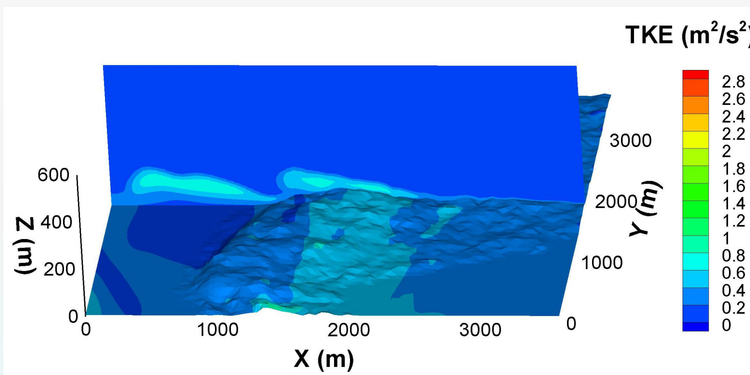


(a)

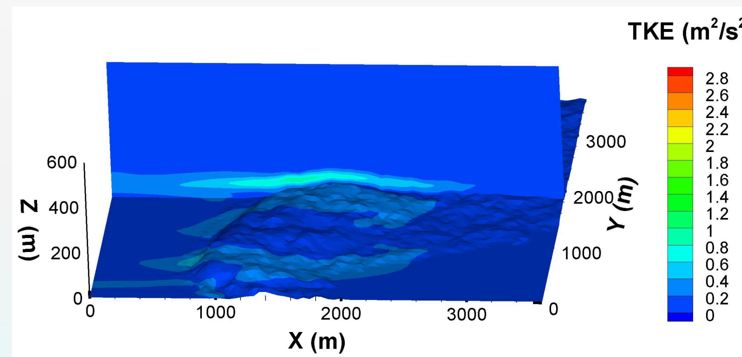


(b)

scheme1



(c)



(d)

14 p.m.

24 p.m.

Fig. 16 Simulation of turbulent kinetic energy distribution, scheme 2 (a) (b), scheme 1 (c) (d)

Summary and Prospect

The main innovation and research results in this paper are as follows:

(1) this paper modifies the traditional RANS turbulence parameterization scheme on the basis of the Fluent model, selects the turbulence scheme of the large eddy simulation (LES), and introduces the physical model of the temperature layer through the UDF (User Defined Functions) interface of Fluent, and obtains the improved Fluent mode and is coupled with the WRF phase. (innovation part)

(2) by using the observation data to compare the simulation results of wind speed and wind direction of the jiishan wind station from December 2010 to 4 months, and compare and analyze the simulated flow field and temperature field at two moments at 14 and 24 on the same day in March 6, 2011, we find that the improved WRF coupled Fluent scheme(scheme 2) has an excellent simulation effect on wind speed and wind direction.

the average error of 70m high average wind speed WRF, calculation scheme 1, and calculation scheme 2, before improvement (calculation scheme 1) and WRF, and 4 months of jiishan station, are 3.963m/s, 2.727m/s and 2.224m/s respectively. In addition, example 2 also simulates the buoyancy effect and the inversion phenomenon at night.

To sum up, this paper improves the existing Fluent model, and explores a WRF coupled Fluent model simulation method (scheme 2) which can more accurately simulate the flow field near the complex terrain (scheme 2). It provides a new method and basis for the prediction of the atmospheric flow field in the atmospheric boundary layer and the multi scale coupling simulation, and also for the future development and the future development. The improvement of the Fluent pattern has laid the foundation.

Problems to be solved further

(1)The WRF driven Fluent mode is unidirectional coupling, and the prediction of WRF is the basis of Fluent prediction. When WRF forecast error is large, Fluent can not be completely corrected.

(2) For the validation of the simulation results of WRF coupled Fluent two schemes, it is necessary to verify the observation data with more intensive and higher sampling rates. In this paper, only the average wind speed data of a single site in Poyang Lake are used.

(3) the improvement of the Fluent model in this paper is an exploratory study. When Fluent is applied to the simulation of the atmospheric flow in the near layer, there are some unsolved problems, such as the low parameters of the underlying surface in the Fluent setting. The coupled simulation problem of water vapor process, the balance between the amount of simulation and the amount of computation. These should be the direction of our further work.

Thank you