Application of MM5 and WRF mesoscale models to studies of regional atmospheric processes

A.V. Starchenko, D.A. Belikov, D.A. Vrazhnov, and A.O. Yesaulov

Tomsk State University
Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk

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Results of application of MM5 (Mesoscale Model 5, http://www.mmm.ucar.edu/mm5/mm5-home.html) and WRF (Weather Research and Forecast, http://wrf-model.org) mesoscale meteorological models to analysis of evolution of local atmospheric processes over the Western Siberia are presented. The considered mesoscale models were realized on multiprocessor computing system with distributed memory at the Tomsk State University and the Institute of Atmospheric Optics SB RAS. The obtained calculation results cover the dynamics of variation of the wind speed and direction, near-ground temperature, humidity, and spatial distribution of meteorological parameters at different moments. For various weather conditions, the predicted parameters were compared with results of meteorological observations over the region of interest.

Introduction

At the present time, to study and predict local atmospheric processes, scientists widely use mesoscale meteorological models,[1,2] which lean on non-stationary three-dimensional equations of atmospheric hydrothermodynamics and parameterization of atmospheric processes (shortwave and longwave radiation fluxes, convective processes, boundary layer, moisture microphysics, atmospheric turbulence, heat and moisture exchange in the underlying surface). Computer implementation of such models is based on application of non-trivial computational algorithms and high-performance computational resources.

At the main world centers (NCAR, EPA, NOAA, NERC), the program source codes of models of such a level for the atmospheric studies are created and freely distributed. In Russia, the use of these models for scientific and applied purposes is limited. This is partly for the lack of relevant computational resources and, sometimes, the lack of specialists. Therefore, it is important to create an extensive information-computational system based on modern models for studies of the physicochemical processes proceeding in the atmospheric boundary layer over a limited territory (urban and regional scales).

In this work, we describe application of some mesoscale meteorological models to the studies of the regional atmospheric processes over Siberia and local ones – over Tomsk. We included in our analysis the models developed at the National Center of Atmospheric Research and widely used by the world scientific community, namely, the Fifth-Generation Mesoscale Model (MM5) and the Weather Research and Forecasting Model (WRF).

Characteristics of the MM5 and WRF models

The Fifth-Generation NCAR/Penn State meteorological modeling system MM5[3,4] is intended for investigations of local and regional atmospheric processes. It can be applied to solving a broad spectrum of theoretical problems of the planetary boundary layer, as well as to predicting meteorological situations in some chosen region. On the meso-beta and meso-gamma scales (2–220 km), the MM5 can be used in studies of atmospheric processes including mesoscale convective systems, passing fronts, dynamics of land–sea breezes, mountain–valley circulations, effects of the urban heat island. Today, MM5 is a meteorological component of the information-computational system Model-3 aimed at solving the problems of predicting the quality of atmospheric air and its optical characteristics.[4]

There are two versions of the model: non-hydrostatic and hydrostatic, which use a surface-tracking coordinate system. The non-hydrostatic model allows the horizontal resolution vary from hundreds of metres to tens of kilometres. The MM5 model includes a possibility to organize calculations in nesting domains with one- or two-way interaction (up to nine consecutively nested domains). Model versions for multiprocessor computers have been developed. There exists also a possibility of four-dimensional assimilation of observational data. In calculations, MM5 generates meteorological fields (the horizontal and vertical components of the wind velocity vector, pressure, temperature, air humidity, cloud and precipitation characteristics, heat and moisture fluxes, short- and longwave radiation fluxes, etc.). The system of equations in the model in the (x, y, σ)-

coordinate system involves equation for pressure p'; motion equation for the velocity components u, v, w; and heat influx equation:

$$\frac{\partial p'}{\partial t} - \rho_0 g w + \gamma p \nabla \mathbf{v} = -\mathbf{v}\nabla p' + \frac{\gamma p}{T}\left(\frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0} D_\theta\right), \quad (1)$$

$$\frac{\partial u}{\partial t} + \frac{m}{p}\left(\frac{\partial p'}{\partial x} - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial x}\frac{\partial p'}{\partial \sigma}\right) = -\mathbf{v}\nabla u +$$

$$+ v\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right) - ew\cos\alpha - \frac{uw}{r_{\text{earth}}} + D_u, \quad (2)$$

$$\frac{\partial v}{\partial t} + \frac{m}{p}\left(\frac{\partial p'}{\partial y} - \frac{\sigma}{p^*}\frac{\partial p^*}{\partial y}\frac{\partial p'}{\partial \sigma}\right) = -\mathbf{v}\nabla v -$$

$$- u\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right) + ew\sin\alpha - \frac{vw}{r_{\text{earth}}} + D_v, \quad (3)$$

$$\frac{\partial w}{\partial t} - \frac{\rho_0}{\rho}\frac{g}{p^*}\frac{\partial p'}{\partial \sigma} + \frac{gp'}{\gamma p} = -\mathbf{v}\nabla w + g\frac{p_0}{p}\frac{T'}{T_0} - \frac{gR_\text{d}}{c_p}\frac{p'}{p} +$$

$$+ e(u\cos\alpha - v\sin\alpha) + \frac{u^2 + v^2}{r_{\text{earth}}} + D_w, \quad (4)$$

$$\frac{\partial T}{\partial t} = -\mathbf{v}\nabla T + \frac{1}{\rho c_p}\left(\frac{\partial p'}{\partial t} + \mathbf{v}\nabla p' - \rho_0 g w\right) + \frac{\dot{Q}}{c_p} + \frac{T_0}{\theta_0} D_\theta. \quad (5)$$

Here $\mathbf{v} = (u, v, w)$ is the wind velocity vector; ρ, p, T, θ are density, pressure, absolute temperature, and potential air temperature (basic values for the standard atmosphere have a "zero" subscript); $p' = p - p_0$; $\sigma = (p - p_\text{T})/(p_\text{S} - p_\text{T})$; $p^* = p_\text{S} - p_\text{T}$, p_S, p_T are surface and upper boundary pressures of the domain; g is the acceleration of gravity; γ is the adiabatic exponent; c_p is air heat capacity at a constant pressure; R_d is the gas constant for dry air; $\dot{Q}$ is the heat influx; m stands for the scale coefficient accounting for inhomogeneity of the underlying surface relief; $e = 2\Omega\cos\lambda$, λ is the latitude; Ω is the Earth angular velocity; f stands for the Coriolis parameter; $\alpha = \varphi - \varphi_\text{c}$; φ, φ_c are the working and central longitudes of the chosen domain; D_u, D_v, D_w, D_θ are the source terms in the corresponding equations.

The model also uses prognostic equations for water vapor and variables of microphysics parameterization such as cloudiness and precipitation. These equations include advection–diffusion and source terms.

The MM5 system allows a large number of parameterization schemes for subgrid physical processes chosen by the user reasoning on requirements of a particular task and the spatial scale of the processes to be modeled.[5] Eight parameterization schemes are provided for convective processes. If the horizontal scale is less than 5 km, then cloud processes are simulated explicitly.

To simulate the processes occurring in the boundary layer, six parameterization schemes are considered, whose applicability is determined by the number of vertical layers in the modeling. Temperature and soil moisture are calculated by one of four suggested parameterization schemes. To simulate radiation transfer in the atmosphere, there are five parameterization schemes. Moisture microphysics is represented by eight schemes having different resolution and applicability.

The WRF (Weather Research and Forecast) model is developed at the US National Center for Atmospheric Research.[6] The WRF can be used to solve a wide range of problems on the scales from hundreds of meters to thousands of kilometres including idealized currents (for example, LES, convection, baroclinic waves); to estimate applicability of different parameterization schemes; to perform comparisons with observation data; to real-time numerical weather prediction. Besides, WRF can be used as a dynamic core in computer modeling systems aimed to investigate admixture transfer and to analyze the atmospheric air quality over urban territories.

The WRF involves non-hydrostatic elastic equations and takes into account surface inhomogeneity. The model also allows one- or two-way calculations in nested domains. It also uses a surface dependent coordinate system; a grid becoming denser in direction to the Earth's surface; conservative difference schemes of the 2nd and 3rd orders of approximation for non-stationary components and 2nd–6th orders for advective components. There exists a parallel version for multiprocessor systems. This model is proved to be more effective than MM5. The main prognostic equations of WRF in the (x, y, z)-coordinate system have the form

$$\partial_t \rho' + \nabla \mathbf{V} = 0, \quad (6)$$

$$\partial_t U + \nabla(\mathbf{v}U) + \partial_x p' = F_U, \quad (7)$$

$$\partial_t V + \nabla(\mathbf{v}V) + \partial_y p' = F_V, \quad (8)$$

$$\partial_t W + \nabla(\mathbf{v}W) + \partial_z p' + g\rho' = F_W, \quad (9)$$

$$\partial_t \Theta + \nabla(\mathbf{v}\Theta) = F_\Theta, \quad (10)$$

where

$$U = \rho u; \; V = \rho v; \; W = \rho w; \;\; \Theta = \rho\theta;$$

$$\mathbf{V} = (U, V, W) = \rho(u, v, w) = \rho\mathbf{v};$$

F_U, F_V, F_W, F_Θ are the source terms in Eqs. (7)–(10).

The pressure is determined from the diagnostic equation of state

$$p = p_0(R_\text{d}\Theta/p_0)^\gamma. \quad (11)$$

Perturbations of the main thermodynamic variables are deviations from time-invariant hydrostatic state:

$$p = p_0(z) + p', \;\; \rho = \rho_0(z) + \rho', \;\; \Theta = \rho_0(z)\theta_0(z) + \Theta'.$$

The WRF model offers many combinable parameterization schemes. It admits different schemes for representing subgrid scale processes: from simple and efficient to complex time-consuming ones; from newly emerging and developing to well tested and widely used in the modern models.[7] To simulate moisture microphysics, eight parameterization schemes are offered differing by fields of applicability and degree of detailing of the atmospheric moisture phase states.

To describe longwave radiation fluxes, there are two schemes, for the shortwave radiation – three schemes. Temperature and moisture of the underlying surface can be calculated with one of three multilayer models of heat and moisture exchange in soil. To represent the parameters of the planetary boundary layer, three parameterization schemes are offered. The same number of schemes is implemented in the WRF model for parameterization of convective processes.

To geographically assign the models (a choice of the domain of interest, accounting for terrain height and the land-use category), global topographic data of different resolution (from 1° to 30″) are used. The initial approximation of meteorologic fields is set using the archive data or data of the previous prediction.

Archive data are taken from the following sources: the reanalysis data of the US National Center for Environmental Protection or the European Center of Mean Weather Forecast; global assimilated NCAR data; data of the regional analysis and prediction.

Initial and boundary conditions for local meteorological fields are set using the objective analysis data. The objective analysis of meteorological fields is performed based on the processing of initial approximation of the meteorological fields and weather data, as well as information on geopotential, wind, temperature, and relative air humidity on isobaric surfaces.

Application conditions for MM5 and WRF models

The meteorological mesoscale models chosen for analysis were used to investigate local atmospheric processes in the south of Western Siberia. For calculations, a domain of 450 × 450 km with Tomsk city in the center (85°E, 56.5°N) was chosen. To obtain a detailed distribution of meteorological parameters around the city, we performed calculations for three nested domains (*D1*, *D2*, *D3*, Fig. 1) with 450 × 450, 150 × 150, and 50 × 50 km horizontal sizes.

Figure 1 shows the domain under study and the arrangement of the land-use categories in it (water, agricultural land, thin vegetation, foliage forest, diverse forest, coniferous forest, urban land). For the nested domains, two-way calculations were performed using parameters for May 16–17, 2004. To set up initial and boundary conditions for the main domain (*D1*), we used the NCAR final analysis data (http://dss.ucar.edu/datasets/ds083.2/data/) with a horizontal resolution of 1° and a periodicity of 6 h. Calculation settings (grids, time and spatial steps, chosen parameterization schemes) are presented in Table.

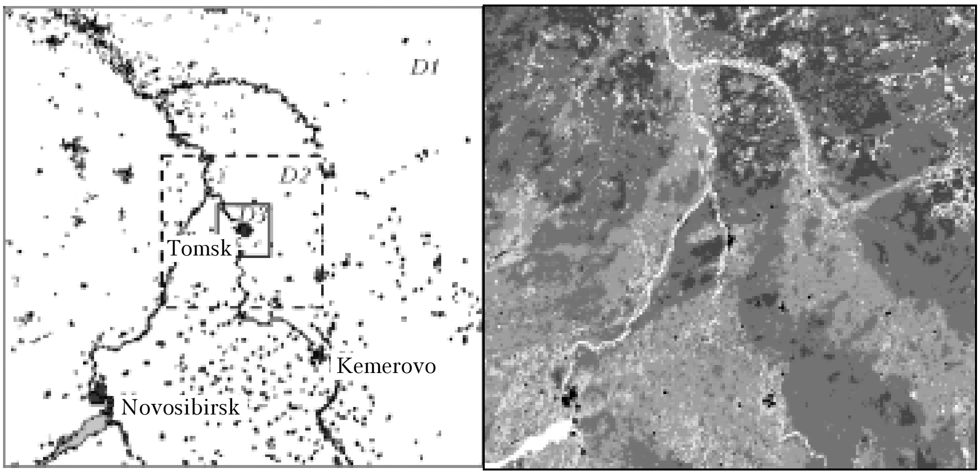

Fig. 1. Land-use categories in the chosen domain.

Table. Calculation settings

Calculation parameters	MM5	WRF
Grids for domains *D1*, *D2*, and *D3*	52 × 52 × 31 grid points	52 × 52 × 31 grid points
Horizontal resolution for domains *D1*, *D2*, *D3*	9; 3; 1 km	9; 3; 1 km
Time step in *D1*, *D2*, *D3*	27; 9; 3 s	60; 30; 10 s
Domain height	17 km	17 km
Computers	IAO computer cluster	IAO computer cluster
	Chosen parameterization schemes	
Microphysics	Mixed phase (Ref. 5)	Ferrier scheme (Ref. 8)
Longwave radiation	RRTM scheme (Ref. 9)	RRTM scheme (Ref. 9)
Near-surface layer	Monin–Obukhov scheme	Monin–Obukhov scheme
Boundary layer	Blakadar scheme (Ref. 10)	Mellor–Yamada–Janjic scheme (Ref. 11)
Soil characteristics	Thermal conductivity equation	Noah scheme
Clouds	Explicit resolution	Explicit resolution

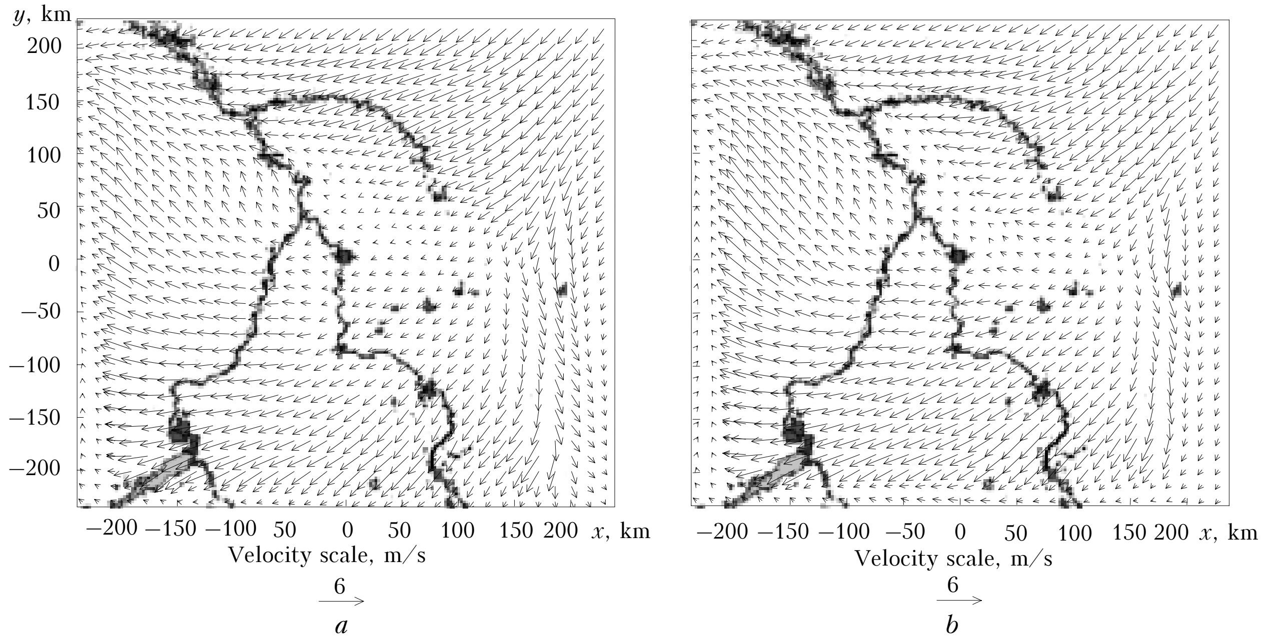

Fig. 2. Surface wind field for *D1* domain (450 × 450 km centered at 85°E, 56.5°N), calculated by the models MM5 (*a*) and WRF (*b*) for May 17, 2004, 8:00 p.m.

Results of model comparison

Figure 2 gives values for wind vector fields at 10 m altitude obtained with the use of the considered models for 8:00 p.m., May 17, 2004 for the *D1* domain (Fig. 1). As is seen, the surface wind takes a turn in this region. The part of the region with the smallest values of the velocity vector module is located to the east of Tomsk. On the whole, there is a good agreement between the results both on wind direction and strength.

Figure 3 shows forecasted surface wind fields above the *D3* domain for the considered time moment (Fig. 1). Calculations show that in this territory, the eastern surface wind direction is dominant. In the right half of the domain, calculations of wind strength and direction have a satisfactory agreement. However, the presence of an extended water channel (the Tom River) crossing the domain from north to south is differently taken into account by the chosen models.

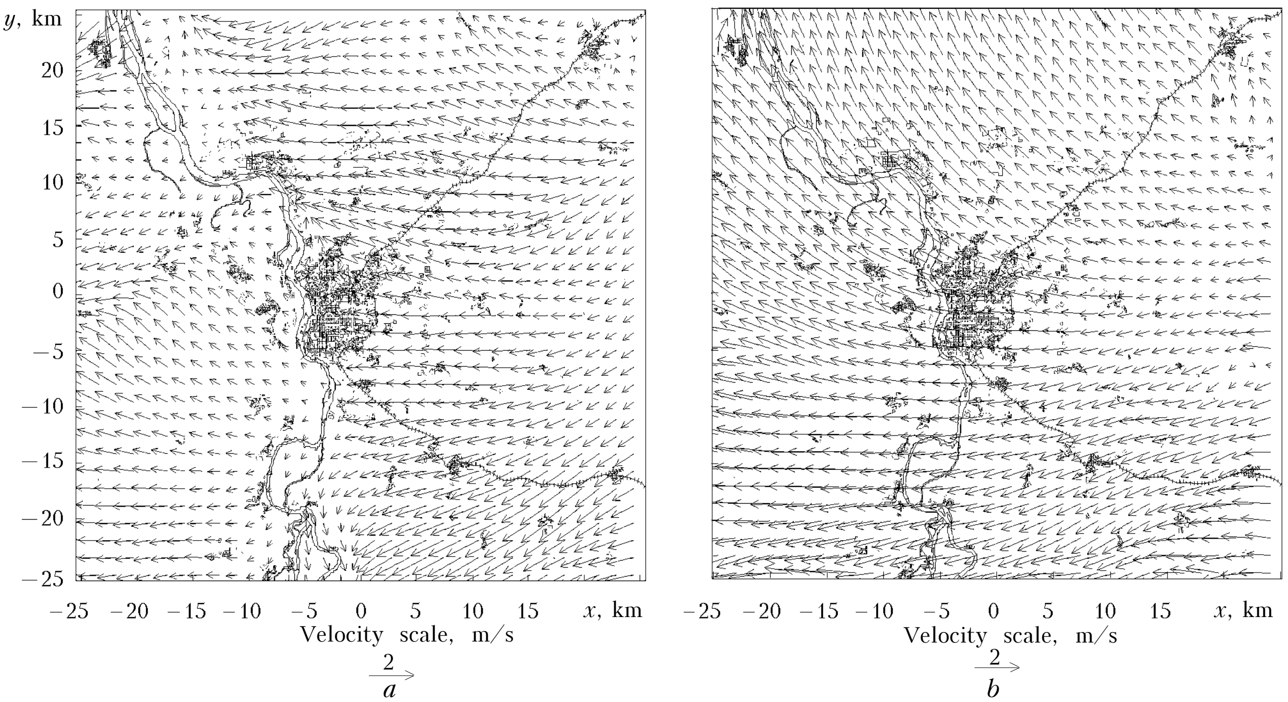

Fig. 3. Surface wind field for the *D3* domain (50 × 50 km, centered at 85°E, 56.5°N), calculated by MM5 (*a*) and WRF (*b*) for May 17, 2004, 8:00 p.m.

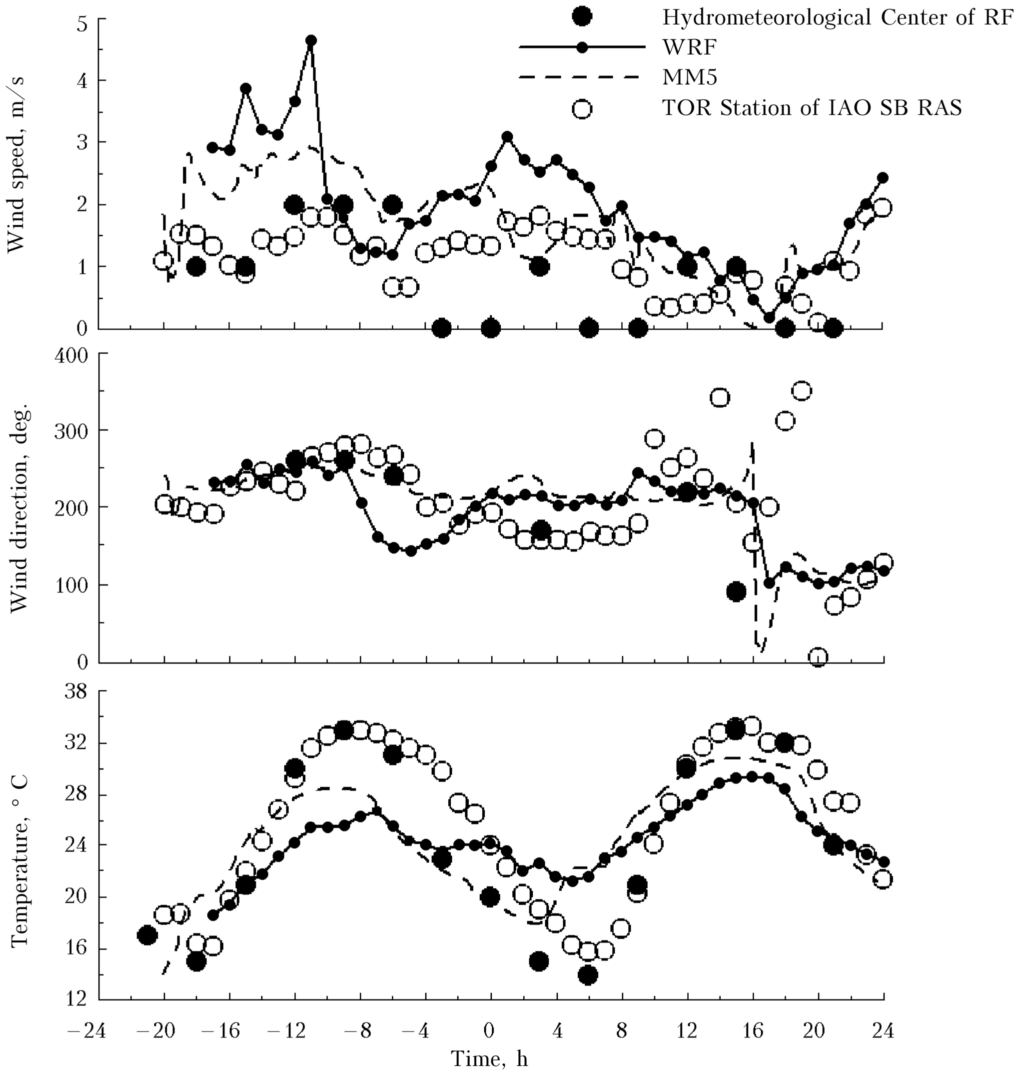

Fig. 4. The change in surface wind speed and direction, as well as surface temperature in Tomsk (85°E, 56.5°N) calculated by MM5 and WRF. Black circles refer to the observation data of the Russian Hydrometeorological Center, white circles are the data obtained at the TOR Station of the IAO SB RAS. Negative values on the time axis correspond to May 16, 2004, positive values refer to May 17, 2004.

For example, the results obtained with WRF model (Fig. 3*b*) show no significant effect of the river in a hollow onto the surface wind field. At the same time, MM5 model data (Fig. 3*a*, on the left) show a decrease of the wind velocity near the river and even its back-turn. Therefore, wind speed module beyond the river is smaller than that resulted from the WRF model, though there is a good agreement in the wind direction. One of the reasons of the divergence between the results is the use of different parameterization schemes of the boundary layer and heat and moisture exchange in the underlying surface.

In Fig. 4, we compare forecasted values of the surface wind speed and direction and air temperature at the altitude of 2 m in Tomsk (85°E, 56.5°N) to the observation data of the Russian Hydrometeorological Center and data obtained at the TOR station of the IAO SB RAS.

Note that we did not carry out the objective analysis of the meteorological parameters because of insufficient number of measurements; and we used the ultimate NCAR data for the first approximation when the model initiation. For this reason, apparently, there is a significant divergence between the forecasted and measured wind speed values for the first day of the modeling period (–24...0 hours, Fig. 4). At the same time, the chosen meteorological models demonstrate a good quality of reproduction of the surface wind direction.

Agreement between the calculated and measured air temperature values is low: the divergence between the diurnal and nocturnal maxima makes 6°. Note that air temperatures calculated by various models differ by not more than 2°.

Conclusion

The results of application of MM5 and WRF mesoscale models are presented. The models are aimed to studies of evolution of local atmospheric processes over the south of Western Siberia and in Tomsk city.

Comparison with the observation data for May 16–17, 2004 have shown that it is possible to apply these models to solving various problems connected with the environmental protection including the prediction of atmospheric air quality, simulation of the technogenic disaster consequences, and obtaining necessary information on atmospheric parameters. However, these models require additional testing in order to find the best adequate parameterization schemes of interaction of the planetary boundary layer with the underlying surface.

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