ISSN 1068-3739, Russian Meteorology and Hydrology, 2011, Vol. 36, No. 12, pp. 777–785. © Allerton Press, Inc., 2011.
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Evaluation of Atmospheric Boundary Layer Characteristics Simulated by the Regional Model

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Received February 25, 2011

Abstract—Carried out is the comparison of the temporal courses of temperature and wind speed at different levels as well as of the wind and temperature profiles in the atmospheric boundary layer obtained from the WRF regional model forecasts and using the upper-air in situ and remote measurements in Moscow region. The errors in temperature and wind speed forecasts at different levels are computed as well as the statistical estimates of the forecast of temperature inversions, atmospheric stratification types, and monthly mean wind speed profiles on the basis of model forecasts and acoustic sounding.

DOI: 10.3103/S1068373911120016

INTRODUCTION

The mesoscale numerical models of atmospheric dynamics are widely used for weather forecasting as a source of meteorological data for the models of pollutant distribution. The investigations of many authors demonstrate that the simulation of different characteristics of the atmospheric boundary layer (ABL) is a matter of considerable difficulties. The greatest difficulties concern the simulation of light wind and turbulence under conditions of stable thermal stratification [14, 17]. In spite of this fact, the comparison of model forecasts with the data of upper-air measurements in ABL in various regions of the world showed their sufficient accuracy (for example, [4, 9, 16]). No such studies have been carried out in Moscow region up to now. In the present paper, an attempt is made to meet this lack.

The description of turbulence in mesoscale models is based on the use of its different parametrizations. The forecast quality is mainly defined by the model configuration including the spatiotemporal resolution and the set of parametrizations of physical processes. Therefore, within the frameworks of the present paper, the influence of ABL parametrization choice on the forecast quality was studied.

The majority of estimates of the model forecast quality are computed for the surface characteristics whereas for describing the exchange processes between ABL and free atmosphere, it is important to know just the quality of the description of vertical distribution of temperature, wind, and humidity. The comparison of numerical atmospheric models of regional scale with regard to the description of ABL and processes near the surface with the measurements within ABL enables to estimate the areas of application and potential of such models.

The measurements in ABL enable to get the information on its structure and dynamics. However, the in situ measurements at the high-altitude meteorological mast and television towers are carried out in sparse points. Besides, the constructions where the measuring instruments are installed also influence the results of such measurements. Recently, in addition to these sparse contact measurements, the remote methods of determining the ABL characteristics were added. The measurements of such type enable to control the ABL state up to the heights of 500–1000 m with high vertical and temporal resolutions.

During the present investigation, the comparison was carried out of wind and temperature profiles in the atmospheric boundary layer obtained in the forecasts of the WRF-ARW regional model (Weather Research Forecast, the United States [15]) with the experimental data of remote sensing using the acoustic sodars and temperature profilers as well as with the data of in situ measurements at the masts in Moscow region.

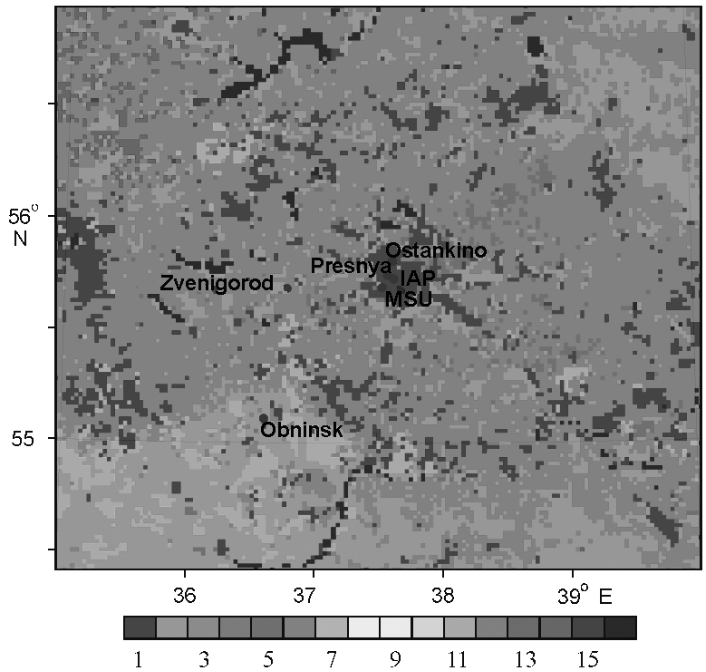

Fig. 1. The simulation domain with indication of underlying surface types and observation points. Designations of types 1–16 correspond to those accepted in WRF model; the following types are found in the domain under consideration: (1) urban development, (2) ploughed fields, (11) deciduous forests, (12) coniferous forests, (15) mixed forests, (6) ploughed fields and forests, (16) water.

FORECASTING MODEL

The computation of meteorological fields was carried out on the basis of the WRF-ARW model. For this purpose, the domain was chosen including in its central part all points for which the data of upper-air measurements are available. In Fig. 1, the modeling domain is presented with the indication of underlying surface types and points with upper-air observations. The horizontal resolution of the model is about 2 km. The horizontal grid of the model is 160×140 points and the center of simulated domain corresponds to the center of Moscow.

As to the vertical direction, 41 σ-levels were specified, 15 of which are within the layer up to 1 km. Such high resolution enables to describe in detail the physical process in ABL. The computations were carried out for each day with the lead time of 60 h and the boundary conditions changed each 6 h. The NCEP analysis data were used as initial and boundary data [11]. Each forecast started at 00:00 UTC. The forecasts of the same lead time were combined to obtain the temporal model series.

PARAMETERIZATIONS OF ATMOSPHERIC PROCESSES

Since there is a possibility to choose the ways of describing the small-scale meteorological processes in present-day models, the understanding how one or another potential parameterization influences the forecast is important when using the model. To separate the effects associated with the ABL parameterization and to search for the optimum configuration of the model, the computations for different days were carried out on the basis of various model versions differing in the choice of the parameterization of ABL and surface layer only. The following parameterizations of atmospheric processes were used for the computations: cloud microphysics [20], long-wave radiation, RRTM [13], short-wave radiation [3], and five-level model of processes in the soil [20]. In WRF model, one of four schemes giving the subgrid vertical turbulent fluxes of momentum, heat, and moisture can be chosen for the boundary layer parameterization.

In the present paper, two different ABL parametrizations and two respective surface layer parametrizations were studied:

1. The parametrization of Yonsei University (YSU) [7] (the forecasts with this parameterization are designated in the text of the paper as “Version 1”) is the modification of MRF (Medium Range Forecast) parametrization [6]. It belongs to the class of so-called nonlocal models [18], is based on the turbulent diffusion equation with addition of the term describing the contribution of large vortices, and takes account of the involvement effect on the upper boundary of ABL [5]. The height of ABL is defined as a height where the minimum flux in the inversion layer exists. Above the mixing layer, the local diffusion equation is used.

The parametrization of the surface layer is based on the equations of similarity theory. In this procedure, the stability functions [2] are taken into account during the computations of exchange coefficients for the heat, moisture, and momentum fluxes. For the realistic description of fluxes, the convective velocity also computed according to [2] is used.

2. Mellor–Yamada–Janjic (MYJ) parametrization [8] (the forecasts with this parametrization are designated as “Version 2”) is based on the system of equations proposed in the paper of G.L. Mellor and T. Yamada [12]. This parametrization of turbulence in the boundary layer and free atmosphere is a version of the fault of turbulence of level 2.5 on the basis of equation of the turbulent kinetic energy (TKE) balance. The upper limit depending on the turbulent kinetic energy as well as on the buoyancy and wind shear is applied to the length scale.

The surface layer model is also based on the similarity theory. It includes the parametrization of viscous sublayer whose impact is taken into account by means of variable roughness when computing the heat and moisture fluxes according to the technique of S.S. Zilitinkevich [19].

It should be noted that all parametrizations use different empirical constants which can greatly depend on underlying surface conditions and, perhaps, their correction for the use in Moscow region can improve the forecast quality in the future.

OBSERVATION DATA

At the high-altitude meteorological mast installed in Obninsk, the measurements of temperature, wind speed, and wind direction at the heights of 8, 121, and 301 m are carried out. This mast is located approximately 100 km to the southwest of Moscow. In Moscow, the sensors of temperature and wind speed are installed at four levels of Ostankino tower (0, 128, 305, and 503 m).

Besides the data of in situ measurements, the data of the remote sensing of ABL are used in the paper as well.

For measuring the profiles of wind speed and wind direction, the LATAN-3 monostatic Doppler sodar [1] installed on the roof of the physical faculty building of the Moscow State University (MSU) is used. The altitude range of sodar sounding reaches 300–500 m above the underlying surface. During July 2005 using this sodar, the measurements were carried out in the countryside near Zvenigorod. The sodar was developed at the Institute of Atmospheric Physics (IAP) of the Russian Academy of Sciences and is also installed on the roof of the building of IAP in the center of Moscow.

The data on the vertical distribution of temperature in ABL were obtained using the MTP-5 microwave temperature profiler [10]. The instrument enables to measure the temperature profiles up to the height of 600 m with the vertical resolution of 50 m. The measurements are carried out at the physical faculty of MSU (Vorob’evy gory) and at the Hydrometcenter of Russia (Krasnaya Presnya) in the center of Moscow.

The values of the height in the text and tables are counted from the height of the instrument installation.

In the paper, the data of remote and in situ measurements of wind speed and temperature for February and August 2007 are used as well as the data of remote measurements of temperature and wind speed for July 2005 in Moscow and near Zvenigorod.

ESTIMATION TECHNIQUE

The point of the model grid being the nearest one to the observation point was taken for the comparison with measurement data. The temperature and wind speed at it were linearly interpolated along the vertical from σ-levels of the model to z-levels, where the measurements are carried out. The processes with small characteristic time are parametrized in the model, therefore, although the measurement data are of greater temporal resolution, it is natural to use the averaged data for the comparison. In the present paper, the half-hour average data of profilers and sodars are used.

Table 1. Average differences between the values of temperature (°C) and wind speed (m/s) predicted using the parametrizations 1 and 2 and observation data

Date, 2007	Measurement point	Height, m										Average value for all heights	
		0		100		200		300		500			
		1	2	1	2	1	2	1	2	1	2	1	2
Temperature													
February 25–26	Obninsk	3.41	3.13	0.27	–0.05	–	–	–0.49	–0.76	–	–	1.06	0.77
	Presnya	–0.34	–0.84	1.45	0.82	1.81	1.15	1.56	1.09	0.68	0.85	1.03	0.61
	Ostankino	0.42	–0.49	0.44	–0.56	–	–	2.38	1.79	0.59	0.54	0.96	0.32
August 23–24	Obninsk	–0.97	–1.80	–2.51	–2.89	–	–	–0.70	–0.58	–	–	–1.39	–1.75
	Presnya	–2.62	–3.35	–1.45	–2.20	–0.52	–0.81	–0.01	–0.17	0.31	0.38	–0.86	–1.23
	Ostankino	–4.01	–3.01	–2.18	–2.08	–	–	–0.92	–0.54	–0.26	0.21	–1.84	–1.35
Wind speed													
February 25–26	Obninsk	2.00	1.33	0.83	0.53	–	–	–0.02	0.05	–	–	0.94	0.64
	IAP	1.03	0.87	1.53	0.77	0.18	–0.09	–	–	–	–	0.87	0.67
	Ostankino	3.17	0.65	1.43	0.60	–	–	1.15	0.70	1.88	1.06	1.91	0.75
August 23–24	Obninsk	1.49	0.55	1.02	1.39	–	–	0.11	0.32	–	–	0.88	0.75
	IAP	2.49	–0.06	2.50	1.37	–0.01	0.51	–4.01	–3.98	–	–	1.81	0.44
	Ostankino	2.76	0.33	2.87	2.46	–	–	4.00	3.54	3.39	3.08	3.25	2.35

COMPARISON OF DIFFERENT PARAMETERIZATIONS OF ABL

In order to choose the ABL parameterization, several days were separated for which the computations with different versions of the model were carried out. Such comparison enables to understand easily and quickly how the parameterization choice influences the simulation result.

The case of February 25–26, 2007 is characterized by the prevalence of western wind of 3–5 m/s, the case of August 23–24, 2007, by the southern wind of 4–8 m/s, and the case of July 4–5, 2005, by the light northern wind.

The differences between the predicted temperature and wind speed and the results of observations were computed for each case at every measurement height. As is clear from the data of Table 1, this difference decreased by 30–50% in a lot of cases at the use of the second version of model configuration. The average difference in temperature between the model computations and observation data for all available points for the winter case decreased from 1.0 to 0.6°C with the second parameterization; it did not change for the summer case and amounted to –1.4°C.

The model describes the main trends of wind speed variations; however, not all peculiarities of the temporal course of wind speed are simulated. The average difference between the model computations and observation data is 1.2 m/s in the first version of the model and 0.7 m/s in the second one for the winter case and 2.0 and 1.2 m/s, respectively, for the summer case.

An important characteristic of atmospheric thermal stratification is the lapse rate. When comparing the surface temperature gradient, it turns out that the model simulated stronger nighttime inversions than it was really observed. For example, when using YSU parameterization (version 1), the unreal strong nighttime inversions can be simulated. At the same time, the second version of the model describes quite realistically the diurnal course of the lapse rate than can be seen in Fig. 2.

Thus, judging by separate but rather heterogeneous cases, the forecasts of the model using MYJ scheme (version 2) describe the temperature and wind in a more realistic way than in the case of using YSU scheme. Therefore, the most part of further computations was carried out using the second version of model configuration.

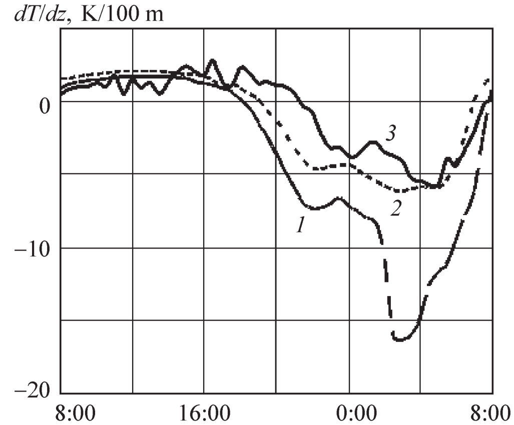

Fig. 2. The diurnal course of surface temperature gradient on July 4, 2005 near Zvenigorod on the basis of two forecast versions (curves *1* and *2*, respectively) and (*3*) profiler data.

COMPARISON OF TEMPERATURE DATA

The analysis of the temporal course of temperature at different levels shows that the model simulates its typical features, the diurnal course corresponds to the measurement data, and its amplitude coincides to within a degree.

As the statistical analysis demonstrates, the difference in temperature between the model and observation data amounts to 1–2°C. The average value of the difference between the model and measured data, the variance of the difference, the absolute error, and the correlation coefficient are given in Table 2.

The forecast for the second day is approximately of the same accuracy as that for the first day. The forecast accuracy for the daytime hours turns out to be slightly higher than for the night.

According to the data of observations in Obninsk, the absolute error of temperature forecast always decreases with height and according to the observation data of Hydrometcenter of Russia, it decreases in winter and increases in summer up to the height of 100–200 m and decreases above this level.

In winter, the temperature in the forecasts is overestimated. In the city the temperature profiles above 100 m are of the same form; the only thing is that the shift towards higher temperatures exists in the model whereas the temperature gradients almost coincide. However, in lower 100-m layer, the situation is different. The average difference between the surface model and measured temperatures is close to zero (although the variance of the difference turns out to be larger that at higher levels). Hence, the surface temperature gradient defining the stability of the layer is smaller in the forecasts than in the measurement data. It can be caused by the fact that the city is a rather strong source of heat influencing considerably the temperature profile but not taken into account in the model.

In summer, the temperature in the model is slightly underestimated. According to the data of Obninsk, the difference between the computed and observed temperatures is about –0.5°C. In Moscow, the average difference above 200 m is close to zero and the absolute error is not larger than 1.3°C. The surface temperature differs considerably from the measurement data, especially in the nighttime hours, when the average absolute error in August amounts to 4°C.

According to the data of measurements and simulation, the average temperature profiles in the country for July 2005 practically coincide. The discrepancies mainly arise in the morning and in the evening.

The model almost always predicts the absence of inversions: if there is no inversion from the observation data, it is also absent in the model in 80–100% of the cases. As to the presence of inversion, it is predicted by the model approximately in the half of the cases in winter and in 75–100% of the cases in summer. The surface inversions in the city are rare: for example, they were not observed in observation data of Hydrometcenter of Russia in February whereas the model predicted them in 14% of the cases.

The vertical temperature distribution defines the stability of the layer; therefore, the simulation of temperature gradients by the model was analyzed. The temperature gradients were classified according to the stratification type:

—stable ($\Delta T/\Delta z > -6.5$ K/km);

Table 2. Estimates of model simulation of temperature (°C) and wind speed (m/s) at different heights

Month	Esti-mate	Obninsk				Ostankino					Presnya (for temperature)/IAP (for wind speed)					
		8 m	121 m	301 m	Average	0 m	128 m	305 m	503 m	Average	0 m	100 m	200 m	300 m	500 m	Average
								Temperature								
February	$\langle\Delta\rangle$	1.86	0.77	–0.36	0.76	0.22	0.23	0.71	0.54	0.67	0.30	1.36	1.61	1.50	1.02	1.21
	$\langle\lvert\Delta\rvert\rangle$	2.15	1.31	0.94	1.47	1.32	1.06	1.05	1.18	1.15	1.31	1.63	1.71	1.60	1.10	1.47
	σ	4.09	1.99	1.35	2.48	2.60	1.69	1.22	1.92	1.86	2.48	1.94	1.61	1.32	0.60	1.59
August	r	0.96	0.97	0.97	0.97	0.96	0.97	0.98	0.96	0.97	0.95	0.97	0.98	0.98	0.99	0.97
	$\langle\Delta\rangle$	–0.21	–0.86	–0.34	–0.47	–1.40	–0.84	–0.23	–0.73	–0.80	–2.06	–0.95	–0.24	–0.01	–0.01	–0.65
	$\langle\lvert\Delta\rvert\rangle$	1.27	1.46	0.85	1.19	1.72	1.24	1.11	1.18	1.31	2.66	1.41	0.82	0.70	0.63	1.24
	σ	2.47	2.67	1.01	2.05	3.56	2.03	1.98	1.48	2.26	8.10	2.46	1.11	0.82	0.63	2.62
	r	0.96	0.96	0.98	0.97	0.94	0.96	0.97	0.97	0.96	0.85	0.95	0.98	0.98	0.99	0.95
								Wind speed								
February	$\langle\Delta\rangle$	1.22	1.35	1.12	1.23	–0.06	2.12	2.62	3.11	1.95	1.48	0.50	0.39	0.32	–	0.79
	$\langle\lvert\Delta\rvert\rangle$	1.28	1.90	2.50	1.89	0.51	2.20	2.78	3.41	2.23	1.59	1.43	1.49	1.87	–	1.53
	σ	0.77	3.39	10.20	4.79	0.39	2.24	4.70	10.56	4.47	1.66	2.96	3.20	5.41	–	2.77
	$\langle\Delta/X\rangle$	1.55	0.58	0.99	1.04	0.15	0.72	0.58	0.66	0.53	0.84	0.41	0.15	0.06	–	0.47
	r	0.74	0.72	0.69	0.72	0.79	0.83	0.86	0.76	0.81	0.64	0.74	0.81	0.82	–	0.73
August	$\langle\Delta\rangle$	0.71	1.01	–0.10	0.54	0.14	1.98	1.63	0.69	1.11	1.42	1.83	1.06	0.12	–	1.34
	$\langle\lvert\Delta\rvert\rangle$	0.92	1.65	1.85	1.47	0.80	2.24	2.15	1.77	1.74	1.54	2.31	2.31	3.13	–	2.14
	σ	0.69	3.16	6.41	3.42	1.54	3.51	4.80	4.78	3.66	1.70	4.81	7.23	13.74	–	5.28
	$\langle\Delta/X\rangle$	2.11	0.56	0.36	1.01	0.71	0.61	0.42	0.25	0.50	2.56	1.18	0.37	0.16	–	1.32
	r	0.65	0.70	0.78	0.71	0.52	0.63	0.73	0.76	0.66	0.34	0.34	0.50	0.45	–	0.39

Note. $\langle\Delta\rangle$ is the average difference model–observations; $\langle\lvert\Delta\rvert\rangle$ is the average absolute difference model–observations; σ is the divergence of the difference; r is the correlation coefficient; X is the average value.

—moist-unstable ($-6.5 > \Delta T/\Delta z > -9.8$ K/km);

—unstable ($\Delta T/\Delta z < -9.8$ K/km).

In Table 3, the data on the coincidence of observed and predicted types of ABL stability are given.

The obtained distributions of temperature gradients demonstrate that the model distribution is wider and is shifted towards smaller gradients, especially in winter.

Thus, the largest discrepancies between the model and observation data in the city are registered in the surface layer up to the height of 150 m.

COMPARISON OF WIND DATA

The average value of the difference between the model and measured data on the wind speed, the variance of the difference, the absolute error, and the correlation coefficient are given in Table 2.

In Fig. 3 presented are monthly mean profiles of wind speed obtained by means of averaging the data of the model and acoustic sounding for February and August 2007 using all data and separately for the nighttime and daytime hours. As they demonstrate, the model overestimates the wind speed at lower levels only, i.e., the vertical wind shear in the model turns out to be smaller than in observation data. The nighttime model and observed profiles differ rather significantly. Although the vertical wind shear at night turns out to be close to the observed one, the profile itself is of different form.

The situation for the wind profiles in winter turns out to be different: the model simulates well the wind speed profile at night but there is a considerably discrepancy with the measurement data in the daytime.

Table 3. Predictability (%) of stratification types

<table>
<tr><th rowspan="2">Point</th><th colspan="5">February 2007</th><th colspan="5">August 2007</th></tr>
<tr><th>0–100 m</th><th>100–200 m</th><th>200–300 m</th><th>300–500 m</th><th>for all heights</th><th>0–100 m</th><th>100–200 m</th><th>200–300 m</th><th>300–500 m</th><th>for all heights</th></tr>
<tr><td colspan="11">Coincidence of stratification types, %</td></tr>
<tr><td>Obninsk</td><td>39.35</td><td colspan="2">43.06</td><td>–</td><td>40.51</td><td>75.00</td><td colspan="2">65.42</td><td>–</td><td>55.63</td></tr>
<tr><td>Presnya</td><td>37.96</td><td>37.50</td><td>56.02</td><td>63.43</td><td>48.73</td><td>61.25</td><td>60.42</td><td>77.08</td><td>66.25</td><td>66.25</td></tr>
<tr><td>Ostankino</td><td>73.15</td><td colspan="2">63.89</td><td>64.81</td><td>67.28</td><td>74.58</td><td colspan="2">68.33</td><td>65.00</td><td>69.31</td></tr>
<tr><td colspan="11">Stable stratification</td></tr>
<tr><td>Obninsk</td><td>36.69</td><td colspan="2">44.90</td><td>–</td><td>41.49</td><td>78.92</td><td colspan="2">90.43</td><td>–</td><td>83.08</td></tr>
<tr><td>Presnya</td><td>81.82</td><td>61.33</td><td>58.82</td><td>67.72</td><td>63.79</td><td>81.72</td><td>82.95</td><td>79.63</td><td>81.36</td><td>81.26</td></tr>
<tr><td>Ostankino</td><td>81.58</td><td colspan="2">90.48</td><td>64.65</td><td>68.98</td><td>86.61</td><td colspan="2">85.71</td><td>64.81</td><td>81.60</td></tr>
<tr><td colspan="11">Moist-unstable stratification</td></tr>
<tr><td>Obninsk</td><td>12.77</td><td colspan="2">11.76</td><td>–</td><td>12.50</td><td>20.00</td><td colspan="2">10.00</td><td>–</td><td>15.56</td></tr>
<tr><td>Presnya</td><td>16.67</td><td>76.74</td><td>63.27</td><td>26.32</td><td>59.83</td><td>3.77</td><td>45.33</td><td>74.67</td><td>24.14</td><td>40.61</td></tr>
<tr><td>Ostankino</td><td>28.57</td><td colspan="2">0.00</td><td>100.00</td><td>22.50</td><td>10.81</td><td colspan="2">7.69</td><td>29.41</td><td>8.27</td></tr>
<tr><td colspan="11">Unstable stratification</td></tr>
<tr><td>Obninsk</td><td>93.33</td><td colspan="2">100.00</td><td>–</td><td>93.94</td><td>89.80</td><td colspan="2">55.56</td><td>–</td><td>65.14</td></tr>
<tr><td>Presnya</td><td>36.18</td><td>2.04</td><td>0.00</td><td>50.00</td><td>24.45</td><td>73.40</td><td>11.11</td><td>0.00</td><td>78.86</td><td>66.41</td></tr>
<tr><td>Ostankino</td><td>79.33</td><td colspan="2">62.63</td><td>–</td><td>70.00</td><td>85.71</td><td colspan="2">69.23</td><td>–</td><td>72.82</td></tr>
</table>

The relative error of wind speed forecast decreases with height. The wind speed at lower levels is overestimated in the model. The difference between the predicted and observed wind speeds is 1–2 m/s. The average difference does not almost depend on the height and the relative error decreases.

The distributions of wind speed at different levels computed from the data of the model and sodar sounding show that the high wind speed occurs more frequently in the model. The model distributions are slightly shifted towards high speeds and are wider. This trend is most pronounced in the lower part of ABL (at the height of 20 and 100 m). Above, the distributions in the area of high speeds turn out to be similar, although, as before, the low wind speed occurs much more rarely in the model.

CONCLUSIONS

The comparison is carried out of results of forecasts based on the WRF-ARW regional model with the observation data in the atmospheric boundary layer. As a result of the analysis, it is possible to conclude that the model simulates satisfactorily enough the average profiles of wind speed and temperature in ABL. The difference in the instantaneous wind speed between the measurements and forecasts can reach 7–8 m/s. The analysis demonstrated an importance of the choice of ABL parameterization in the forecast of profiles of meteorological variables. The Mellor–Yamada–Janjic parameterization turned out to be the most successful for Moscow region [8]. The proposed method of comparison of the vertical structure of meteorological variables with the observation data enables to choose the set of parameterizations of physical processes in the model being the most suitable for the certain task.

The largest deviations of simulated values of temperature and wind speed are registered in the lower part of ABL in the urban environment. As the researches of other authors show, a particular type of atmospheric boundary layer requiring the special description is formed in the city. The data obtained during the research can serve as a basis for improving the forecast of temperature and wind in the atmospheric boundary layer and their estimates.

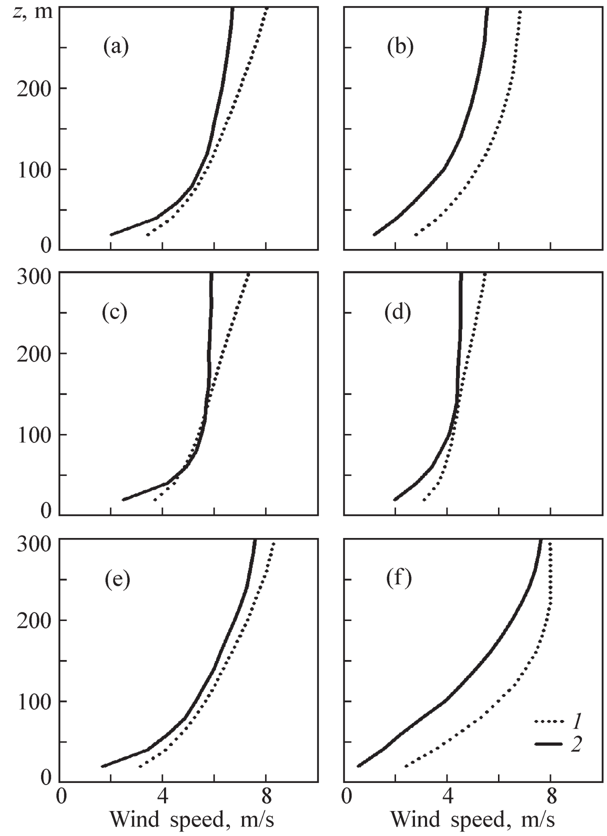

Fig. 3. The average profiles of wind speed for (a, c, e) February and (b, d, f) August 2007 from the data of (*1*) model and (*2*) sodar computed for (a, b) all data and separately for (c, d) daytime and (e, f) nighttime hours.

ACKNOWLEDGMENTS

The study was partially supported by the Russian Foundation for Basic Research (grants 08-05-00984, 08-05-13545-ofi_ts, 09-05-00652-a, and 10-08-00493-a).

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