Advanced Model of Atmospheric Boundary Layer

V. Shnaydman (volf@envsci.rutgers.edu) and G. Stenchikov
Rutgers University, New Brunswick, NJ
L. Berkovitch
Russian Hydro-meteorological Research Centre, Moscow

In this study an advanced turbulent closure scheme is used to improve simulation of 3-dimensional distribution of meteorological variables and turbulence characteristics in atmospheric boundary layer (ABL). It included two transport equations for turbulent kinetic energy and dissipation rate [*Shnaydman and Berkovitch*, 2006]. This closure scheme is superior with respect to the Mellor-Yamada closure. Similar schemes are used in the advanced computational fluid dynamics codes like FLUENT [*Huber et al*., 2004; *Lesieur, et al*., 2002]. The advanced ABL model explicitly describes effect of large eddies. Medium range anisotropic eddies are handled by Smagorinsky model, and effect of small inertial-range eddies is calculated using two-equation closure parameterization of *Shnaydman*, [2004].

The advanced ABL model has been coupled with the hemispheric forecast model of the Russian Hydrometeorological Center [*Shnaydman and Berkovitch*, 2006]. The results were obtained for the meteorological conditions of the USA, Canada (20-55ºN, 70-125ºW), and Europe, Central Russia. The calculation period was 36 hours with initial time 00:00 UTC April 12, 2005. Here we conduct a detailed analysis of vertical distribution of meteorological variables and turbulence parameters.

The most intensive turbulent exchange was obtained for noon hours. The dominant mechanism of the turbulent mixing was the strong non-stable thermal stratification. The intensive turbulent exchange restricted vertical gradient of horizontal wind in the layer from 100 m till the ABL top of 1200 m. Under these conditions the maximal values of turbulence coefficient (K_z), turbulent kinetic energy (TKE) and dissipation rate ε reached, respectively 65 m^2/s (at z=300m), 2.3m^2/s^2 (at z= 100m), and 0.06 m^2/s^3 (in roughness layer). By using the values of TKE and ε in the Kolmogorov-Prandl relationship the vertical length (L) and time (τ) scales could be calculated. The maximal spatial and temporal scales were equal to 47 m and 332 s, respectively. This value of turbulence length scale corresponds to the inertial interval of the TKE spectrum. The product of time scale to the speed of horizontal motions gave a horizontal length equals approximately to 5 km. The vertical length calculated using speed of organized vertical motions appeared to be about 100 m. The associated anisotropy coefficient of 0.02 in the boundary layer is two times larger than in the free atmosphere.

The weakest turbulent exchange was found for night hours. The forcing mechanism of the turbulent mixing for these conditions was interaction of stable stratification and turbulent exchange. The ABL top was at 300 m only. The maximal values of K_z, TKE and ε were 8.0 m^2/s, 0.96 m^2/s^2 and 0.012m^2/s^3, respectively. The maximal length and time scales were 12 m and 125 s, respectively. Vertical and horizontal lengths were 2 km and 30 m, and the anisotropy coefficient was about 0.015.

Mean values of turbulence characteristics and their limits under different meteorological conditions were calculated for different temperatures and wind stratifications. The typical ABL turbulence parameters for selected ranges of vertical temperature gradient and wind shear are given in the tables 1, and 2.

Table 1. Typical ABL parameters for selected ranges of vertical temperature gradient

Stratificatio n deg/100m	Kz m^2/s	L m	Limits Kz L	TKE m^2/s^2	τ s	Limits TKE τ
< - 2.0	41	33	31-65 31-48	1.8	228	1.0-3.2 250-310
-2.0 --- -1.0	28	24	21-43 23-27	1.4	200	0.8-2.5 172-262
- 1.0 --- 0.0	13	15	6-20 9-18	0.6	185	0.4-0.8 150-250
> 0.0	5	9	1-12 3-10	0.3	167	0.1-0.4 100-200

Table 2. Typical ABL parameters for selected ranges of wind shear

Stratificatio n m/s per 100m	K_z m^2/s	L m	Limits Kz L	TKE m^2/s^2	τ s	Limits TKE τ
> 2.0	30	20	20-43 17-24	2.1	143	1.4-3.2 134-176
2.0 --- 1.0	9	10	5-22 6-17	0.9	100	0.6-1.6 83-137

The predicted ABL internal structure calculated within the forecast model was tested against the ABL adapted to the characteristics of the free atmosphere obtained from operational objective analysis. The simulated driving characteristics in the 24 hours forecast at the bottom and at the top of ABL were in good agreement with the operational objective analysis. The predicted values inside the ABL agreed with adapted parameters which were obtained from the stationary solution of the closed system of hydrodynamic and closure scheme equations and the objective analysis fields as the boundary conditions. The predicted and adapted variables had similar vertical distributions and differences in wind magnitude and direction were 0.8 m/s and 12-18°. The differences in vertical temperature gradients were 0.2-0.3° per 100m. Thus, the relative error in simulated turbulent parameters did not exceed 20%.

We found that the developed model eliminates the main shortcomings of Mellor-Yamada description of ABL internal structure. It is more physically consistent because it simultaneously accounts for the impacts of large, intermediated and small eddies, and describes the locally isotropic sub-grid turbulence. The results of application in the Russian Hydro-meteorological Research Centre operational forecasting reveal the effectiveness of ABL modeling and downscaling in the numerical prediction operations.

References

Huber, A., Tang, W., Flowe, A., Bell, B., Kuehlert, K., and Schwarz, W., 2004: Development and Applications of CFD Simulations in Support of Air Quality Studies Involving Buildings. Preprints, 13th Joint Conference on the Applications of Air Pollution Meteorology, US EPA.

Lesieur, M., Metais, O., Compte, P., 2002: Large-Eddy Simulations in Turbulence, Cambridge U. Press, New York, 219pp

Shnaydman, V., 2004: Improved Hydrodynamical Scheme of Turbulence Description, Research Activity in Atmospheric and Oceanic Modeling, No 34, and 4.29-4.30.

Shnaydman, V., Berkovitch, L.,2006: Atmospheric Boundary Layer Modeling in the Numerical Prediction Operations, Research Activity in Atmospheric and Oceanic Modeling, No 36, 5.57-5.57