22.2 IMPROVEMENTS TO SURFACE FLUX COMPUTATIONS IN A NON-LOCAL-MIXING PBL SCHEME, AND REFINEMENTS TO URBAN PROCESSES IN THE NOAH LAND-SURFACE MODEL WITH THE NCAR/ATEC REAL-TIME FDDA AND FORECAST SYSTEM

Yubao Liu[1*], Fei Chen[1], Tom Warner[1], Scott Swerdlin[1], James Bowers[2] and Scott Halvorson[2]
[1]National Center for Atmospheric Research/RAP, Boulder, Colorado
[2]U.S. Army Dugway Proving Ground, Dugway, Utah

1. INTRODUCTION

For support of materiel testing at U.S. Army test ranges, the National Center for Atmospheric Research (NCAR) and the Army Test and Evaluation Command (ATEC) have been jointly developing a real-time multi-grid (with grid sizes of 0.5 - 45 km), four-dimensional data assimilation and forecast (RTFDDA) system. The system has been running operationally at five Army test ranges for 2 - 3 years. It was designed to cycle at time intervals of 1 - 12 hours, with each cycle producing analyses and 3 - 48 hour forecasts. The high-resolution, real-time analyses and forecasts from the RTFDDA system have become a dependable tool in the daily operational meteorological support of tests at the Army test ranges. In addition, RTFDDA has been used to support missions of other DOD and government agencies. Among these missions was the Joint Urban 2003 Atmospheric Dispersion Study (JU2003), held in Oklahoma City, Oklahoma, in July 2003. Considerable effort is being devoted to improving the RTFDDA data assimilation methods and model physics schemes (Liu et al. 2002). This paper reports on our recent modifications to the model PBL parameterization, which significantly improves the surface flux computation, and refines the urban-substrate physical processes. Results of case studies and the RTFDDA operation during JU2003 are presented.

2. MODIFICATIONS TO MRF PBL SCHEME

2.1 Problems in the Current MRF PBL Scheme

The NCAR/ATEC RTFDDA system is based on the Penn State University (PSU)/NCAR MM5 mesoscale model. The Hong and Pan (1996) PBL scheme (commonly referred to as MRF scheme) and the OSU (Oregon Sate University) land surface model (OSULSM), which was recently replaced by the newly-developed Noah land- surface model, are employed to model boundary layer and soil-layer physics. The MRF PBL scheme, which is widely used in the MM5 community in research and operational mesoscale weather forecasting, was selected for use in the RTFDDA system for its efficiency and its reasonably good performance in modeling precipitation. One of the known problems of the PBL scheme is that it tends to overestimate the daytime PBL growths and, hence, seriously underestimates the surface winds. For example, Cheng et al. (2003) reported that the MM5 simulations with the MRF PBL scheme persistently overpredicted the PBL height over the Houston-Galveston area. By conducting sensitivity experiments with five PBL parameterizations in MM5, for a case with 3 consecutive clear-sky days over the Central Plains, Zhang and Zheng (2003) found that all PBL schemes underestimated the daytime surface winds, and the MRF scheme performed the worst. Zhang and Zheng pointed out that there is a general lack of understanding of the PBL momentum-transport processes, owing to the fact that previous research on PBL and LSM modeling was focused on thermal and moisture fluxes only.

Statistical verification of the surface analyses and forecasts of the RTFDDA operational systems revealed the same problem at all five Army ranges in all seasons. Fig.1 shows the bias errors of 10-m AGL wind speed for the RTFDDA10-12 hour forecasts on the fine mesh (1.1 - 3.3 km grid, depending on the range), as verified against the range mesonet observations in August, 2002. Although there exist large geographical and climatological differences among the ranges, the RTFDDA forecasts at all ranges underpredict the wind strength during the daytime. The RTFDDA analysis could be forced to correct the wind bias, but the correction would not survive long into the forecast.

The summer daytime PBL is characterized by free-convective mixing of sensible and latent heat, as well as momentum. Winds near the surface are controlled by the downward mixing of the larger momentum from above, and the upward mixing of lower momentum from below. Under free-convection conditions, thermal instability in the surface layer induces extra mixing in the surface layer, which enhances the surface heat, moisture and momentum fluxes. The increased surface momentum flux suppresses the momentum in the surface layer. Apparently, the underprediction of daytime surface winds results from either an underestimate of the downward momentum flux or an overestimate of surface stress. Previous speculation (e.g. Zhang and Zheng, 2003) leaned toward the former. Our recent analysis of the RTFDDA model output reveals that this problem is mainly in the computation of the free-convection eddy mixing in the surface-flux parameter-

* Corresponding author address: Yubao Liu, National Center for Atmospheric Research, P. O. Box 3000, Boulder, CO 80307-3000. Phone: (303) 497-8211 Email: yliu@ucar.edu

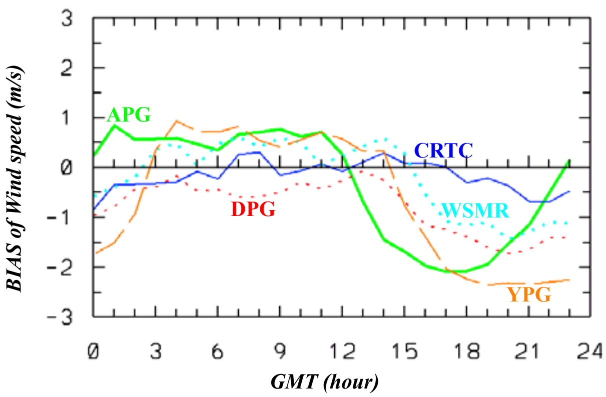

Fig.1 The average surface wind speed bias of the 10 - 12 hour forecast of the RTFDDA systems on fine meshes in August 2002 at five Army test ranges: Aberdeen Proving Ground, Cold Region Test Center, Dugway Proving Ground, White Sands Missle Range and Yuma Proving Ground.

ization.

As with most other PBL parameterizations, the MRF PBL scheme calculates the surface-layer fluxes based on Monin-Obukhov similarity theory,

$$\overline{W'\theta'} = C_h|U| (\theta_g - \theta_a) \quad (1)$$
$$\overline{W'q'} = C_q|U| (q_g - q_a) \quad (2)$$
$$u*^2 = C_m |U|^2 \quad (3)$$

where |**U**| is the mean length of the horizontal wind vector ($U^2 = u^2 + v^2$), the subscripts **g** and **a** denote ground-level (soil skin) and the first (lowest) model level, respectively, and other variables have their conventional meteorological meaning.

The extra eddy mixing induced by surface-layer free-convective instability is parameterized by replacing the mean length of the horizontal wind vector |**U**| in Eqs. (1)-(3) with **Uc,** which enhances |**U**| with a so-called "convective velocity", **W*,** component:

$$U_C^2 = U^2 + (\beta W*)^2. \quad (4)$$

Physically, U_C represents the wind that is measured by a cup anemometer in free-convection conditions, and βW* represents how much wind is measured in free-convection condition when the horizontal wind vector is zero (Beljaars, 1994). The inclusion of the **W*** in the surface mixing formulations enhances the surface heat and moisture fluxes, and increases the surface momentum consumption by turbulence.

In the standard MRF PBL scheme, β is set to unity and **W*** is computed based on the difference in the virtual potential temperature between the soil surface and the first model layer:

$$W* = C (\theta_{vg} - \theta_{va})^{0.5} . \quad (5)$$

Here, **C** is an empirical constant. The **W*** formulation in (5) seems to capture the basic free-convective mixing effect due to thermal instability. However, careful analysis exposes a few problems. First, it is evident that the depth of the lowest model layer, where θ_{va} is defined, will affect the **W*** calculation. However, it is not uncommon for modelers to change the model levels from one model application to another. In addition, the sigma coordinate in the MM5 system varies horizontally with terrain height. Also, different soil models may define surface skin temperature differently, resulting in a significantly different virtual potential temperature at the "surface" (θ_{vg}). For example, in a SLAB soil model the skin is represented by the uppermost soil layer, whereas in the Noah land-surface model the "skin" represents the infinitely thin layer at the top of the soil. This would result in a difference of ~10 K in θ_{vg}, which would directly affect the **W*.** Also, the square-root scaling in the formulation is very questionable. In summary, the **W*** formulation in (5) was neither built on sound theory nor is it capable of adapting to the variety of possible model configurations and associated physics schemes. Although the parameter **C** may be adjusted, it is apparent that it cannot deal with the many complexities mentioned above. In fact, the constant **C** was set to 2.0 many years ago in the MM5 system, when only the SLAB soil model was available. This setting, of course, is not compatible with modern MM5 systems, where the OSU and Noah LSMs are used and a very thin lowest model layer is specified.

An analysis of RTFDDA results confirms the problem of the **W*** formulation in Eq. (5). On a normal day with clear skies, MM5 simulations with the Noah LSM scheme and the lowest model level at ~15 m AGL can produce differences in θ_{vg} and θ_{va} of 10 - 25 C during the daytime. For a difference of 16 C, Eq. (5) will yield a **W*** of about 8 ms^{-1}, which is larger than |**U**| in most weather situations. This will lead to an overestimate of the friction velocity (**u***), resulting in excessively weak surface winds. And, with the excessively weak surface winds, the free-convective mixing (**W***) becomes even more dominant in the surface-layer flux computation.

2.2 Incorporating Beljaars' Formulation

To solve the problem of the poor surface momentum flux representation, a more sophisticated surface flux formulation (Beljaars, 1994) was implemented. In Beljaars' formulation, the **W*** is computed directly from the surface sensible and latent heat fluxes, and the PBL height:

$$W* = (z_i \overline{W'\theta'}_v g/T)^{1/3} \quad (6)$$

where z_i is the mixing layer (PBL) height, **g/T** represents buoyancy and $\overline{W'\theta'}_v$ is the sum of the surface sensible and latent heat fluxes ($\overline{W'\theta'_v} = \overline{W'\theta'} + 0.61\theta_v\overline{W'q'}$). This new **W*** formulation is more physically based because the **W*** is directly linked to the heat flux and PBL depth, which controls the convective turbulence and PBL development. Unlike in Eq. (5), the **W*** formulation in Eq. (6) does not depend on the questionable parameter **C**, the specification of the lowest model layer depth, and the definition of the soil skin. Furthermore, in Beljaars (1994), the **W*** formulation in Eq. (6) was carefully calibrated with the LES simulation by Sykes et al. (1993). In fact, all parameters in Eq. (6) are physical variables, and should not be adjusted arbitrarily. What Beljaars calibrated is the parameter β in Eq.(4), which expresses the relation between **Uc** and **W***, and represents how much wind will be observed by an anemometer in free convection, given a **W***. According to Beljaars' calibration, β varies with the mixing layer depth between 0.8 and 1.3, from deep to shallow PBLs. In these RTFDDA applications, β is set at 1.1.

2.3 A New Method for Calculating the PBL Height

From Eq. (6), an accurate computation of **W*** will still rely on accurate computation of the mixing-layer height and the surface heat and moisture fluxes. Recall that one of the known problems with the original MRF PBL scheme is its overestimate of the PBL height. Case studies with the RTFDDA system indicate that the MRF PBL scheme frequently produces premature PBL development (1-3 h) and excessively deep PBLs (a few hundred meters to more than 1 km) in the morning. These PBL height errors not only affect the PBL thermodynamic structure, but also directly result in overestimation of **W*** according to Eq. (6). In order to improve the surface flux computation in the free-convection PBL, the MRF PBL height needs to be improved.

In the original MRF PBL scheme, the PBL height is diagnosed with a bulk Richardson number ($\mathbf{R_{ib}}$) in a layer between the surface and a model level above. The surface is defined as a level on which winds are assumed calm, and the thermal state is defined by both the surface heat flux and the virtual temperature at the lowest model level. PBL heights are defined by comparing the $\mathbf{R_{ib}}$ with the critical Richardson number ($\mathbf{R_{ic}}$), which is set at 0.25. Searching from the bottom up, when the $\mathbf{R_{ib}}$ of the layer between the surface and a model level is found to be larger than $\mathbf{R_{ic}}$, the PBL height is defined to be equal to the height of the model level, plus an increment that is defined by upward extrapolation based on the difference between the $\mathbf{R_{ib}}$ and $\mathbf{R_{ic}}$. This approach seems consistent with the non-local mixing strategy of the MRF PBL scheme, however it is subject to a few problems. First, wind shear may vary greatly with height in the lowest 1-3 km, and sometimes wind maxima can be observed within a PBL. Second, there exist phase (time) lags between the evolution of the surface thermal state and the PBL structure, and therefore the model surface thermal state may be subject to some phase and/or amplitude errors. Thus, the $\mathbf{R_{ib}}$ in a layer between the surface and a model level may not be a good indicator of the turbulence in the layer. And, the $\mathbf{R_{ib}}$ may not represent the turbulence near the PBL top at all, and thus using $\mathbf{R_{ib}}$ to extrapolate the PBL height will by no means be accurate.

We introduce a new approach to improve the PBL height calculation. Instead of using the deep-layer bulk $\mathbf{R_{ib}}$, the new approach estimates PBL heights by using a local bulk Richardson number ($\mathbf{R_{ibl}}$). The $\mathbf{R_{ibl}}$ is computed for each model layer based on the wind shear and thermal stability between two neighboring model levels. Like the old approach, the PBL height is determined by instability-searching from the bottom-up. However, here the $\mathbf{R_{ibl}}$ is compared with the $\mathbf{R_{ic}}$. When $\mathbf{R_{ibl}} > \mathbf{R_{ic}}$ is found for a model layer, the PBL height is set to the height of the top of the layer, plus an adjustment obtained by using the same extrapolation method as before, but with $\mathbf{R_{ibl}}$. In contrast to the $\mathbf{R_{ib}}$, the $\mathbf{R_{ibl}}$ represents the local state of the model layers in the model PBL, and thus can better trace the PBL development. In addition, since the $\mathbf{R_{ibl}}$ is local, its value in the top layer of the day time growing PBL will represent the local turbulence property of the layer. So, the final step in the PBL height calculation is more accurate. Using the new PBL height computation, a sudden, short-term, natural or artificial, change of the surface thermal state will not cause the PBL height to change. In contrast, in the old scheme, the PBL height would change.

It is of interest that using the local $\mathbf{R_{ibl}}$ to estimate PBL heights is conceptually consistent with the approach in more complicated, higher-order PBL turbulence closure schemes, where PBL heights are diagnosed based on turbulence kinetic energy (TKE) which is predicted at the model grid points. These local TKE values represent the intensity of the local turbulence, which is similar to $\mathbf{R_{ibl}}$. Numerical experiments run on the same cases with different PBL parameterizations showed that the PBL heights calculated with the revised MRF PBL scheme are very close to those diagnosed by the more sophisticated but more costly Meller-Yamada-Janjic scheme (not shown).

2.4 Incorporate Zilitinkvich's heat exchanges

Surface heat and momentum fluxes possess opposite signs - the heat fluxes are upward while the momentum fluxes are downward. In the original similarity theory, the roughness length for the heat flux is considered to be the same as that for momentum flux. Zilitinkvich (Chen et al. 1997) refined the formulation of the surface heat flux in the similarity theory to consider the difference between the thermal and momentum roughness lengths. This scheme was introduced into MM5 by Chen and Dudhia (2001). It is restated here because it is of great importance to incorporate this refinement along with the

MRF PBL modifications described previously.

3. MODIFICATION TO NOAH URBAN SCHEME

Correctly modeling urban effects on the atmosphere was crucial for the success of the RTFDDA support for the Joint Urban 2003 Field Experiment in Oklahoma City (OKC). Its large urban area has a strong impact on the dynamic and thermal structures of the PBL, and hence on the transport and dispersion of airborne material over the city. RTFDDA analyses and forecasts were used as input for atmospheric dispersion models and for planning of the field experiments. In the high-resolution RTFDDA configuration, the urban area occupies roughly 20% of the 1.5-km grid and 70% of the 0.5-km grid (see Fig.2). The current Noah land surface model in MM5 (Chen and Dudhia, 2001) has a very simplified urban representation, which merely increases the roughness length and reduces surface albedo for the urban land-use category. Eventually, we plan to couple an advanced, one-layer, urban-canopy model, based on Kusaka et al. (2001), with the Noah LSM, and implement them into mesoscale models. Given the time constraints for preparing for the 2003 field program, we adopted an intermediate approach by which the current Noah LSM was enhanced to capture the primary influences of the urban area.

The Noah LSM urban enhancements included: 1) increasing the roughness length from 0.5 m to 0.8 m to account for the turbulence generated by roughness elements and drag due to buildings; 2) reducing the surface albedo from 0.18 to 0.15 to represent the shortwave radiation trapping in the urban canyons; 3) using a larger volumetric heat capacity of 3.0 J m^{-3} K^{-1} for the urban surface (walls, roofs, and roads) which usually consists of concrete or asphalt materials; 4) increasing the value of soil thermal conductivity to 3.24 W m^{-1} K^{-1} to parameterize the large heat storage in the urban surface and underlying surfaces; and 5) reducing the green vegetation fraction over the urban area to decrease evaporation.

4. CASE STUDY AND JU2003 OPERATION

4.1. Results From the Modified MRF PBL Scheme

Research on the MRF PBL scheme and Noah urban-process modifications was conducted during the preparation stage of the JU2003 field operation. A period with clear skies over the Central Plains, from May 26 to 28, 2003, was chosen to evaluate these modifications. The case was selected because both PBL growth and urban effects are largest during these conditions, although these modifications can be applied in all weather situations, and were employed during the JU2003 operation in July 2003. Five nested-grid domains were used, with grid sizes of 40.5, 13.5, 4.5, 1.5 and 0.5 km, respectively (Fig.2). The RTFDDA system was cycled every 3 hours, and in each cycle a 3-hour final analyses and a 15-hour (or longer) forecast was generated. The model physics, aside from the MRF PBL scheme and Noah LSM scheme, were the same as those described in Liu et al. (2002). The RTFDDA analyses and forecasts were verified against hourly surface observations and 12-hourly radiosondes. Here, only the surface verification of the analyses and 10-12 h forecasts are presented.

Simulations were conducted to verify the new PBL height calculation scheme using the clear-sky case of May 28, 2003. The model results indicate that the new approach leads to a great improvement in the estimate of PBL heights. To demonstrate the results, the PBL height evolution, calculated based on the new and old methods for May 28, 2003, is compared

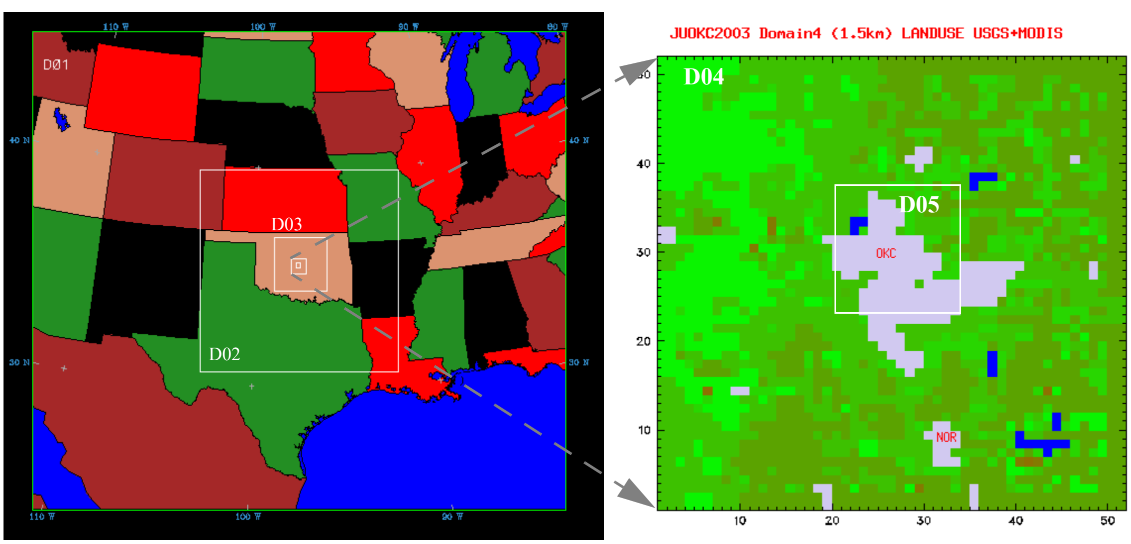

Fig.2 JU2003 RTFDDA domain configuration and land use on Domain 4

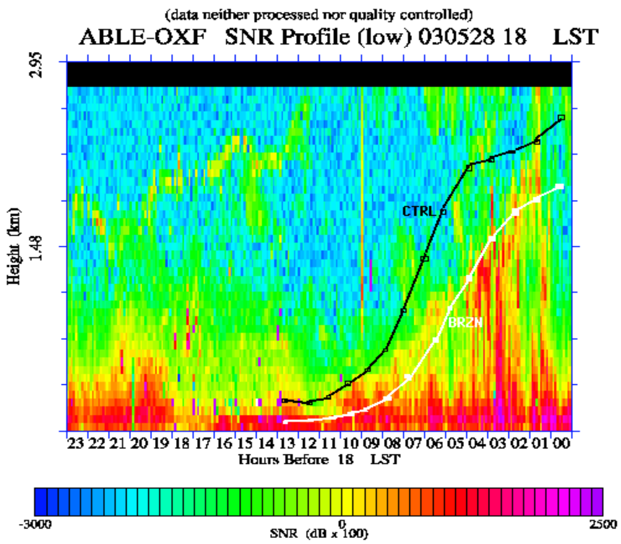

Fig.3 PBL height evolution from the RTFDDA simulation on May 28, 2003, with the old (CTRL, black) and revised (BRZN, white) PBL height diagnostic schemes at the ANL Oxford profiler station.. The color shadings denote the signal-noise ratio observed by the Oxford wind profiler.

with wind-profiler observations made by three profilers located in Kansas and operated by the Argonne National Laboratory (ANL). It is known that the low-power signal-to-noise ratios of the wind profilers capture PBL turbulence properties. The PBL heights predicted from the RTFDDA model were interpolated to the wind profiler stations. Fig. 3 shows the comparison of the PBL-height evolution of the RTFDDA model runs and estimates from the ANL profiler located at Oxford, KS, from 11 to 23 UTC on May 28, 2003. The PBL calculated with the old approach develops too early, and becomes too deep during the daytime. In contrast, the new approach performs much better. Similar results were observed at the other two profiler stations (not shown).

After evaluating the new PBL height scheme, comparison experiments with the RTFDDA system were conducted for a 3-day period between 00 UTC May 26 and 00 UTC May 29, with the original (old) and the modified (new) MRF PBL schemes. Fig. 4 shows the average surface wind-verification statistics on Domain 1 of the two experiments. The original scheme seriously underestimates daytime surface winds, with a maximum bias of -2.5 m/s at around 20 UTC for the 10-12h forecasts and -1.6 m/s for the final analyses. These wind biases are also evident in the wind speed RMS error plot (Fig. 5), with a peak during the daytime. In contrast, the modified MRF PBL scheme is able to effectively reduce

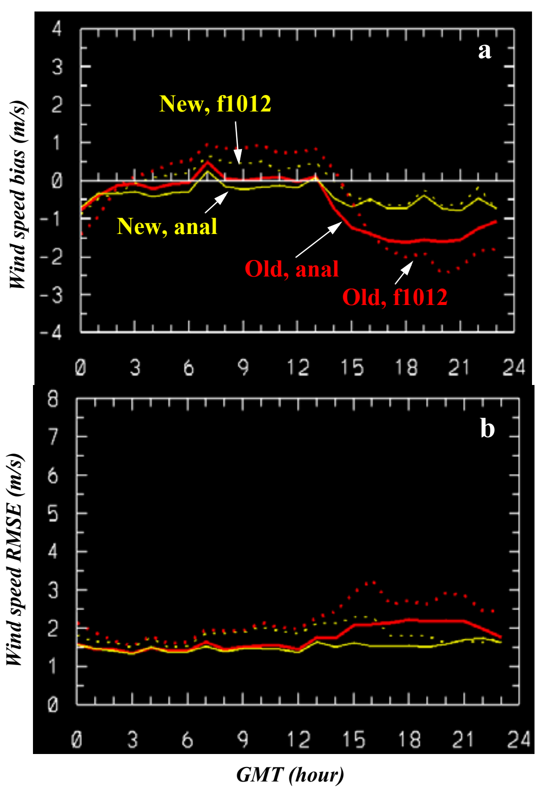

Fig.4 Diurnal evolution of surface wind bias (a) and RMS (b) of the RTFDDA analyses (solid lines) and 10 - 12h forecasts (dotted lines), with the original (red) and modified (yellow) MRF PBL schemes, averaged on Domain 1.

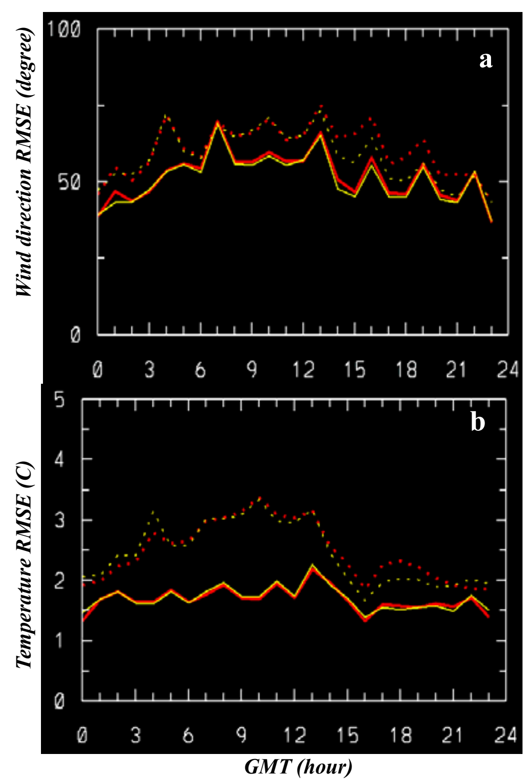

Fig.5 Same as Fig.4, but for RSM errors of wind direction (a) and temperature (b)

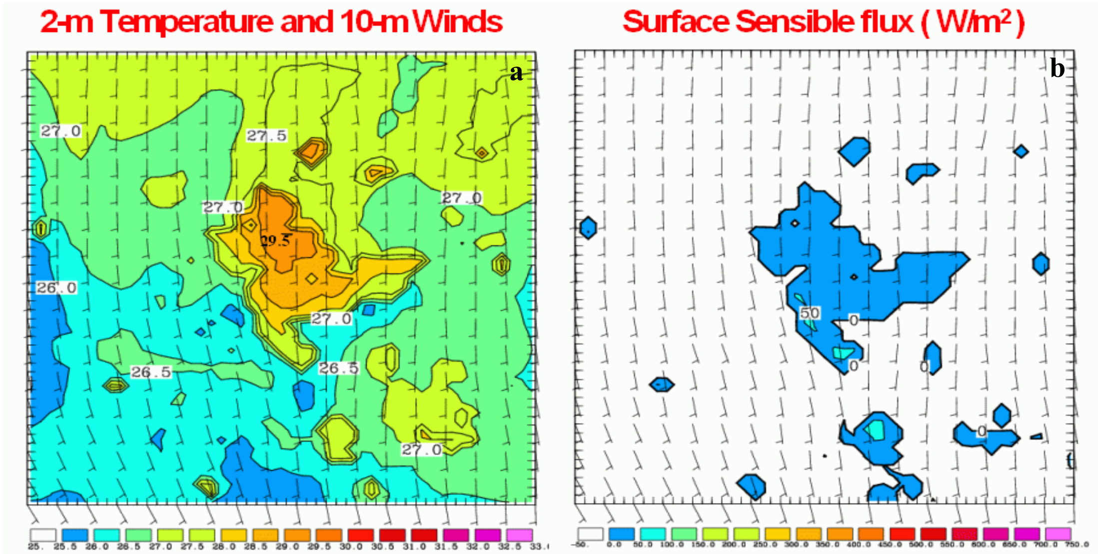

Fig.6 Average 2-m temperature (a) and surface sensible heat flux (b) on Domain 4, valid at 06Z (about the local midnight), on 9 clear-sky days during the JU03 in July, 2003

these daytime weak-wind biases by 70%. In addition, the new scheme also improves the nocturnal wind speed forecast. The RMS-error plot shows that the revised MRF PBL scheme exhibits a similar error magnitude for both the daytime and the night time.

Although the major goal of the MRF PBL modification is to correct the daytime weak-wind bias at the surface, the other surface variables also benefit from the modifications. Fig.5 shows that the new MRF PBL scheme, together with the Zilitinkvich's approach, significantly improve the daytime and early-evening surface wind direction, temperature, and moisture (not shown) predictions. The night-time wind speeds and directions are also slightly improved. As with the model forecasts, the RTFDDA analyses also show some gain in accuracy. The observed improvement to all the model variables leads to a better overall simulation of the daytime PBL. Finally, verification results for the finer meshes of the RTFDDA system are very similar to those for Domain 1. Domain 1 is chosen for display here because of much larger volume of surface observations available on it.

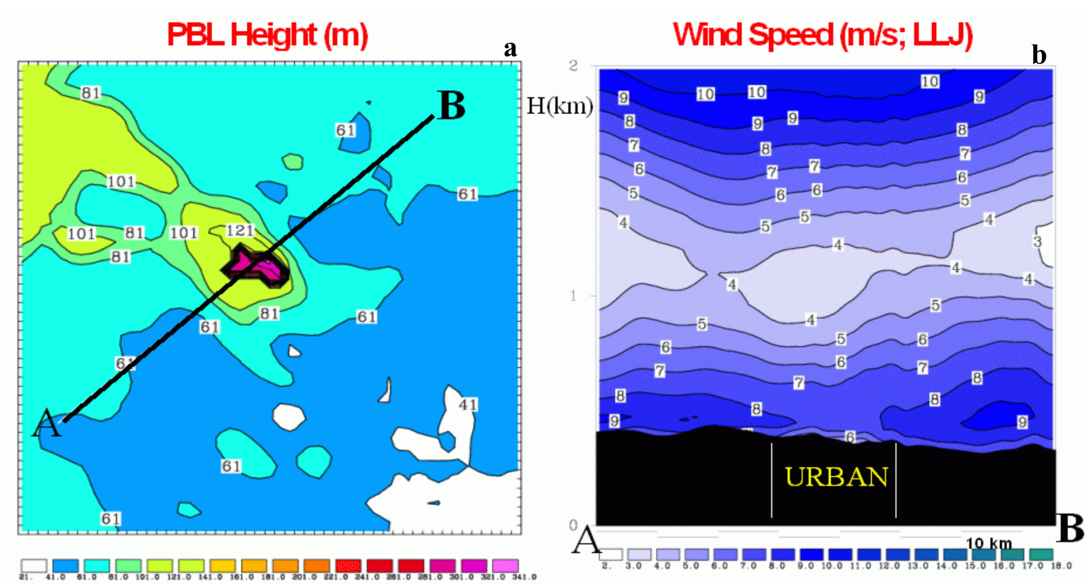

Fig.7 PBL height on Domain 4 (1.5-km mesh, a) and LLJ structure (b) of a cross section along line the AB, valid at 06 UTC July 24, 2003

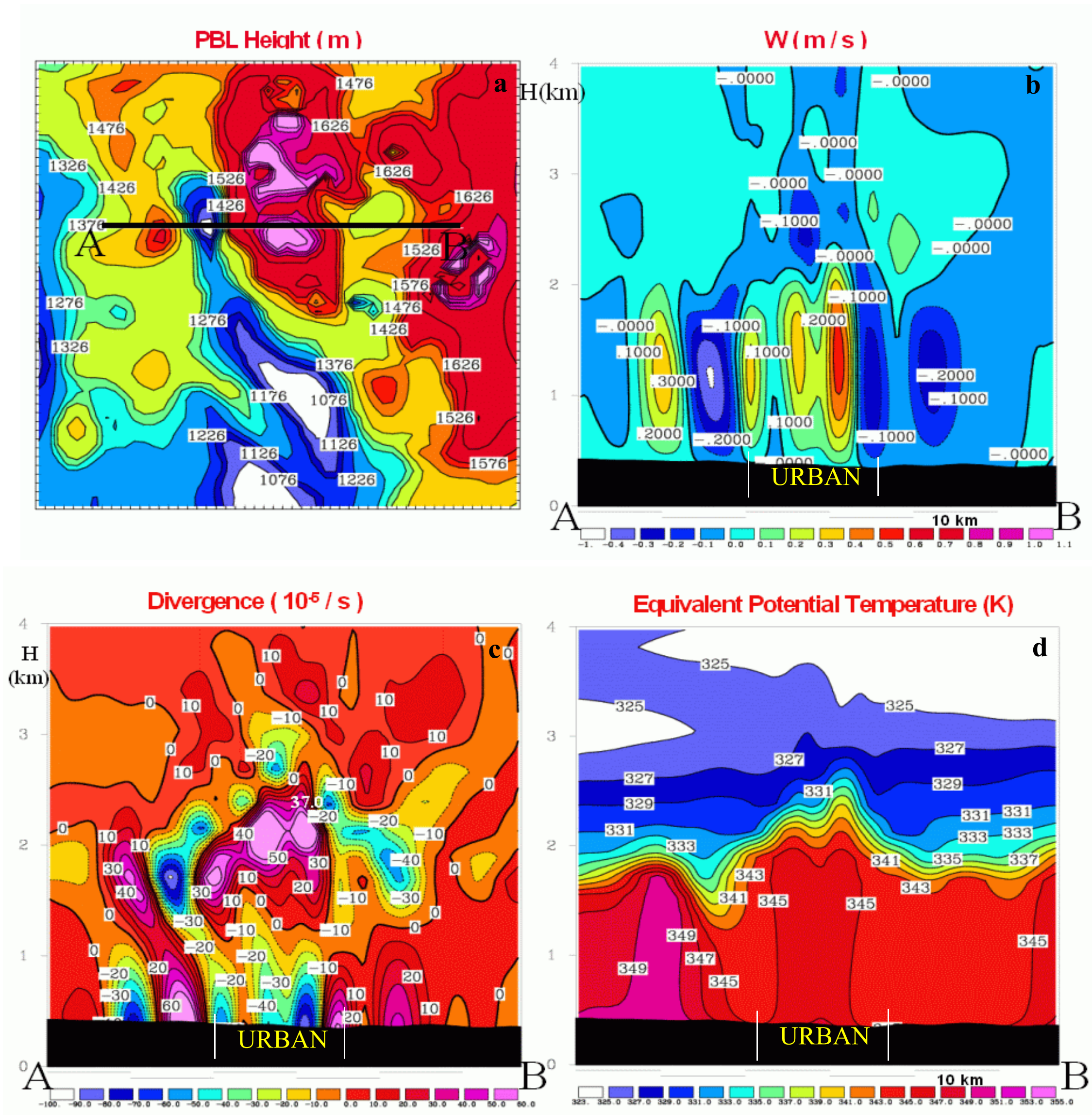

Fig.8 Same as Fig.7, but for PBL height (a) and vertical cross sections of vertical motion (b), divergence (c) and θe (d) along the line AB, valid at 18 UTC, July 5, 2003

4.2. Results from the Modified Noah Urban Model

Initial work on the Noah urban model modification was also carried out with pre-JU2003 cases. We have not yet been able to gather sufficient special observations in the OKC center-city urban area to quantify the model results there. Instead, the average performance of model runs, which incorporated the Noah urban-scheme modifications during JU2003 operations, will be evaluated for a couple of cases.

RTFDDA analyses on Domain 4 for nine clear-sky days during the JU2003 experiment were selected and averaged. The urban heat island effects are apparent in the 9-day average of 1.5-km grid RTFDDA forecasts (Fig. 6), with the OKC area being roughly 2-3 C warmer than the rural regions (Fig. 6a). Note that, in Fig 6b, this nocturnal urban heating is able to keep the lower boundary layer slightly unstable (with heat transferred from the surface to the atmosphere), while the surrounding rural areas are mostly in the stable regime because of the surface inversion.

Examination of daily RTFDDA forecasts revealed a more pronounced influence of the urban landuse on the atmosphere. For instance, the PBL height over the core OKC urban region was about 100 meters higher than that over the rural regions at 06 UTC (local midnight) on July 24, 2003 (Fig. 7a). Due to stronger mixing in the nocturnal urban mixed layer, and hence less decoupling of the surface layer with the atmosphere, the strength of the nocturnal low level jet (LLJ) over the OKC urban area is weaker than that in the surrounding areas (Fig.7b).

Large differences between urban and rural areas were also seen for daytime PBL development. Shown in Fig. 8 is the 1.5-km grid PBL height, and cross-sections of vertical wind speed, equivalent potential temperature, and horizontal divergence, valid at 18 UTC (about local noontime). The daytime PBL height over the OKC area was about 300 to 500 meters higher than that over rural areas, and organized mesoscale circulations seem to develop as a result of differential heating and pressure gradients between the urban and rural areas, forming convergence (divergence) in the lower (upper) PBL over the urban region. This influx of moisture from the more-moist rural areas, into the strongly mixed boundary layer over the urban area, makes the urban entrainment zone more humid.

5. SUMMARY

The widely-used MM5 MRF PBL scheme has been revised to reduce the known problems of the under-prediction of daytime surface winds and the overprediction of PBL heights. More-realistic methods for computation of free-convective turbulence, PBL height, and surface heat flux were developed and incorporated into the MRF PBL scheme. The modified MRF PBL scheme not only improves the PBL-height prediction and reduces the daytime surface wind bias, but also improves surface thermal and moisture variables as well. The benefits also extend to the night time.

In conjunction with the high-resolution RTFDDA operation during JU2003 over the OKC area, the Noah land surface model was enhanced to more properly represent urban moist processes, heat-trapping and storage, and roughness. These urban landuse enhancements in the Noah LSM appear to capture at least the zero-order urban effects in the RTFDDA analyses and forecasts.

REFERENCES

Beljaars, A., 1994: The parameterization of surface fluxes in large-scale models under free-convection. *Q. J. R. Meteorol. Soc*., **121**, 255-270.

Chen, F., and J. Dudhia, 2001: Coupling an advanced land-surface/hydrology model with the Penn State/NCAR MM5 modeling system. Part I: Model implementation and sensitivity. *Mon. Wea. Rev.*, **129**, 569-585.

Chen, F., Z. Janjic and K. Mitchell, 1997: Impact of atmospheric surface-layer parameterizations in the new land-surface scheme of the NCEP mesoscale ETA model. *Bound. Layer. Meteor*., **85,** 391-421,

Cheng, F., D. Byun and S. Kim, 2003: Sensitivity study of the effects of land surface characteristics on meteorological simulations during the TexAQS2000 period in the Houston-Galveston area, 13th PSU/NCAR Mesoscale Model Users' Workshop, June 10 -11, Boulder, CO.

Cram, J.M., Y. Liu, S. Low-Nam, R-S. Sheu, L. Carson, C.A. Davis, T. Warner, J.F. Bowers, 2001: An operational mesoscale RT-FDDA analysis and forecasting system. *Preprints 18th WAF and 14th NWP Confs*., Ft. Lauderdale, AMS, Boston, MA.

Hong S.-Y. and H.-L. Pan, 1996: Nonlocal boundary layer vertical diffusion in a Medium-Range Forecast model. *Mon. Wea. Rew.*, **124**, 2322-2339.

Kusaka and co-authors, 2001: A Simple Single-Layer Urban Canopy Model For Atmospheric Models: Comparison With Multi-Layer And Slab Models. Bound. Layer Meteorol., 101, 329-358

Liu, Y. and co-authors, 2002: Performance and enhancements of the NCAR/ATEC mesoscale FDDA and forecasting system. *15th Conference on numerical Weather Prediction* , San Antonio, Taxes, 12-16 August, 2002, 399-402.

Stauffer, D.R., and N. L. Seaman, 1994: Multiscale four-dimensional data assimilation. *J. Appl. Meteor., **33**, 416-434.*

Sykes, R.I., D. Henn and W. Lewellen, 1993: Surface-layer description under free-convection conditions. *Q. J. R. Meteorol. Soc*., **119**, 409-421.

Zhang, D.-L. and W. Zheng, 2003: Diurnal Cycles of Surface Winds and Temperatures as Simulated by Five Boundary-Layer Parameterizations. *J. Appl. Meteor.* (submitted).