Simulations of the Urban Planetary Boundary Layer in an Arid Metropolitan Area

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ABSTRACT
A modified version of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) was applied to the arid Phoenix, Arizona, metropolitan region. The ability of the model to simulate characteristics of the summertime urban planetary boundary layer (PBL) was tested by comparing model results with observations from two field campaigns conducted in May/June 1998 and June 2001. The modified MM5 included a refined land use/cover classification and updated land use data for Phoenix and bulk approaches of characteristics of the urban surface energy balance. PBL processes were simulated by a version of MM5’s Medium-Range Forecast Model (MRF) scheme that was enhanced by new surface flux and nonlocal mixing approaches. Simulated potential temperature profiles were tested against radiosonde data, indicating that the modified MRF scheme was able to simulate vertical mixing and the evolution and height of the PBL with good accuracy and better than the original MRF scheme except in the late afternoon. During both simulation periods, it is demonstrated that the modified MM5 simulated near-surface air temperatures and wind speeds in the urban area consistently and considerably better than the standard MM5 and that wind direction simulations were improved slightly.

1. Introduction
Phoenix, Arizona, is the second-fastest-growing major city in the United States and is shifting from a mid-sized regional center to one of the nation’s largest metropolitan areas. Average annual population growth in the past 10 yr amounted to 4.1%, which represents a change in population from about 2.5 to 3.5 million people in the greater Phoenix region. The current size of the built-up urban area is about 3500 km² (GP2100 2003).

Urbanization significantly affects regional near-surface air temperatures, wind fields, and the evolution of the planetary boundary layer (PBL), modifies local circulations, and subsequently influences air quality, human comfort, and health (Cotton and Pielke 1995; Fernando et al. 2001). Mesoscale atmospheric models are increasingly employed to improve the understanding of these processes that are strongly influenced by the energy and momentum exchange between the atmosphere and the underlying surface. The quality of the simulations depends on characterizing the urban and rural land cover accurately and characterizing the physical approaches of processes related to the urban surface energy balance and PBL.

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The goal of this study was to test the ability of a modified version of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (NCAR) Mesoscale Model (MM5) to simulate characteristics of the urban PBL for the arid Phoenix metropolitan region under typical summer conditions of the desert Southwest, which are characterized predominantly by high pressure systems with weak synoptic-scale forcing.

The modified version of MM5 used in this study included a refined land cover classification and updated land use/cover data for the Phoenix region as well as bulk approaches for characteristics of the urban surface energy balance such as increased heat storage flux, the production of anthropogenic heat, and radiation trapping (Grossman-Clarke et al. 2005). The nonlocal closure Medium-Range Forecast Model (MRF) boundary layer scheme (Hong and Pan 1996) was replaced by the version of the MRF scheme described by Liu et al. (2006). MM5 with the original MRF scheme (Hong and Pan 1996) has been shown to simulate the atmospheric boundary layer in the southwestern United States better than do other available PBL schemes in MM5 (Bright and Mullen 2002). However, there is a tendency for the MRF scheme to underestimate near-surface wind speeds and to overestimate sensible heat fluxes and boundary layer heights under free-convection conditions (Zhang and Zheng 2004; Liu et al. 2006). The model’s behavior is caused by the empirical description of the convective velocity and was discussed in detail in Liu et al. (2006). To resolve problems of poor surface momentum flux representation in the original MRF scheme, Liu et al. (2006) introduced a formulation of the convective velocity by Deardorff (1972) and Beljaars (1995) and replaced the bulk Richardson number that is used in the PBL height calculations by a local Richardson number.

In a previous study (Grossman-Clarke et al. 2005), it was shown for a 3-day simulation period that these changes to MM5 considerably improved the regional response of the near-surface meteorological variables. However, the influence of the modifications to MM5 on the simulated evolution of the urban PBL and the model performance for near-surface variables over a longer time period were not tested. To use the modified version of MM5 in future studies to analyze the effect of urbanization on meteorological processes in the region with higher confidence, its performance was evaluated by comparing the models’ outputs with surface meteorological data, upper-air radiosonde data, and radar wind profiler data from two field campaigns conducted in May/June of 1998 (Fast et al. 2000) and June of 2001 (Doran et al. 2003) in the Phoenix metropolitan area, spanning an extended time period of 53 days.

2. Data, model, and analysis methods

a. Design of numerical simulations

MM5, version 3.7, was employed for the two simulation periods of the two field experiments: 10 May 1998–10 June 1998 and 10–30 June 2001. The simulations were carried out in 72-h increments, allowing 24 overlapping hours for model spinup. The runs were started at 0000 UTC [1700 local standard time (LST)]. Nested simulations with four domains, with horizontal grid spacings of 54 km (3294 km east–west by 2700 km north–south), 18 km (1350 km east–west by 1080 km north–south), 6 km for domain 3 (594 km east–west by 414 km north–south), and 2 km for domain 4 (212 km east–west by 132 km north–south).

Fig. 1. Location of the four MM5 modeling domains as used in this study. Grid spacings are 54 km for domain 1 (3294 km east–west by 2700 km north–south), 18 km for domain 2 (1350 km east–west by 1080 km north–south), 6 km for domain 3 (594 km east–west by 414 km north–south), and 2 km for domain 4 (212 km east–west by 132 km north–south).
cluded by using the original and modified versions of
the nonlocal closure MRF scheme (Hong and Pan 1996;
Liu et al. 2006). The 5-layer soil model (Dudhia 1996)
was enhanced by bulk approaches for characteristics of
the urban energy budget as described in section 2b.

Four-dimensional data assimilation (FDDA) was ap-
plied to the grid with a 54-km spacing over the 72-h
duration of the 1998 simulations to improve MM5’s
ability to describe the observed trend in the maximum
2-m air temperature $T_{2m}$ over the simulation period. It
was shown in Grossman-Clarke et al. (2005) that
FDDA did not change the differences in the maximum
simulated $T_{2m}$ between the land cover scenarios by
more than 1 K and that therefore it could not compen-
sate for deficits in the model’s surface energy balance as
mediated through land use/cover, which led to consid-
erably larger differences of about 4 K in the simulated
$T_{2m}$. FDDA was used in MM5 through three-dimen-
sional analysis nudging for wind and temperature; that
is, forcing functions were added to the governing equa-
tions to nudge the model state gradually toward the
observations (Grell et al. 1995).

### b. Model description

The spatial extent, nature, and heterogeneity of ur-
ban land cover across the rapidly urbanizing arid Phoe-

FIG. 2. Land use and terrain (m) as produced by MM5’s TERRAIN preprocessor for the inner modeling domain (2 km × 2 km) based
on Landsat Thematic Mapper 1998 image-derived land use/cover data and three urban land use/cover classes: urban built-up, urban
mesic residential (irrigated), and urban xeric residential (arid, partly irrigated). Other land use/cover categories were the same as in
the standard MM5 24-category USGS dataset. Sites labels for radar wind and radiosonde profilers are 1 for Sky Harbor Airport, 2 for
McDowell Mountain Park, and 3 for Waddell. Coordinates are given as universal transverse Mercator zone 12 (UTM12) easting and
orning.

with MM5, which includes only one urban land use/cover type (Guo and Chen 1994) and reflects the region
as of the 1960s. Therefore, as described in Grossman-
Clarke et al. (2005), a new land cover classification was
developed using land use data derived from 1998
Landsat Thematic Mapper satellite images (Stefanov et
al. 2001). Two additional urban land cover classes were
introduced into the existing 24-category USGS land
cover classification used in MM5 to give three urban
categories: urban built-up, urban mesic residential, and
urban xeric residential, which were distinguished by the
type of vegetation and irrigation (no vegetation, well-
watered flood or sprinkle irrigated, and drought-
adapted vegetation with drip irrigation, respectively).
The land cover distributions and contours of terrain for
the inner domain (2 km × 2 km grid spacing) as gen-
erated by MM5’s “TERRAIN” preprocessor, based on
the USGS 30-s land use data, are given in Fig. 2. The
urban/suburban core is surrounded by irrigated agricul-
tural land and a dry, sparsely vegetated natural desert
that is assigned as shrubland category 8 in the USGS
classification.

Characteristics of the urban energy balance that con-
tribute to increased nighttime temperatures are anthro-
pogenic heat production, sky-view factor in the long-
wave radiation balance, increased surface volumetric
heat storage capacity, and thermal conductivity. A de-
tailed description of physical parameter choices for the
urban land use classes was given in Grossman-Clarke et
al. (2005). A value of 0.85 was determined for the sky-
view factor of the urban land use categories. We adopted the approach of Sailor and Lu (2004) to calculate hourly profiles of anthropogenic heat based on resident and working population density data, electricity consumption, and vehicle miles traveled. Urban-induced modifications on the momentum exchange between the atmosphere and the surface were included through adjustments in the aerodynamic roughness length.

To evaluate the performance of the modified MRF scheme in this study for the Phoenix area, PBL processes were included in the simulations through use of the original and modified MRF schemes. In both versions of the MRF scheme, the nonlocal- $K$ approach by Troen and Mahrt (1986) is used, which represents large-eddy turbulence within the well-mixed boundary layer by incorporating a correction to the local gradient of the prognostic variables in the turbulence diffusion equation.

In the original MRF scheme by Hong and Pan (1996), the PBL height $h$ is calculated as a function of a critical bulk Richardson number, $Ri_{cr}$, the horizontal wind speed at $h$ $U(h)$, and the virtual potential temperatures at the lowest prognostic level ($\theta_w$), at the PBL height [$\theta_s(h)$], and at the surface ($\theta_v = \theta_w + \theta_f$, with $\theta_f$ being the virtual temperature access near the surface):

$$h = Ri_{cr} \frac{\theta_w |U(h)|^2}{\theta_s(h) - \theta_f}.$$  

Problems arise under convective conditions from an overestimation of the friction velocity and therefore very weak surface winds (Zhang and Zheng 2004) and an overestimation of PBL heights (Liu et al. 2006) and subsequent vertical mixing. This situation is due to the fact that $h$ appears in the profile function used to calculate diffusivity coefficients under convective conditions (Hong and Pan 1996).

To improve the surface momentum flux representation in the MRF scheme, Liu et al. (2006) introduced a formulation of the convective velocity $w*$ that was described by Deardorff (1972) and further studied by Beljaars (1995). The convective velocity is added to the magnitude of the mean wind vector in the surface flux calculations to consider extra eddy mixing induced by surface-layer free-convective instability. Furthermore, in the modified MRF scheme, the PBL height is determined by using a local bulk Richardson number $Rib$ that is computed for each model layer based on wind shear and thermal stability between two neighboring model levels. Instability searching from the bottom up is applied by comparing $Rib$ with a critical Richardson number, $Ri_c = 0.25$; if $Rib > Ri_c$ is found for a model layer, the PBL height is set to the height of the top of the layer plus an adjustment that is obtained by upward extrapolation based on the difference between $Rib$ and $Ri_c$.

c. Experimental data

Phoenix is located in the center of the Salt River valley at a mean elevation of about 335 m above sea level. There is typically little synoptic forcing in the desert Southwest during the spring, early and late summer, and autumn months, which are generally dry. The focus of this study was on the latter conditions when thermal flows due to horizontal pressure gradients caused by complex terrain as well as potential mesoscale circulations due to land use/cover variation are the dominant climatological features and determine the local winds.

A meteorological and atmospheric-chemistry field study was carried out in the Phoenix metropolitan area from 10 May to 10 June 1998 to study the convective PBL. The details of the experimental sites and instrumentation were described in Fast et al. (2000). The relevant sites for this study for the 915-MHz radar wind profiler are shown in Fig. 2 and included 1) Sky Harbor Airport (elevation 350 m) and 2) the rural McDowell Mountain Park (elevation 616 m). Each profiler was configured to operate in a high-resolution mode with 60-m range gates and a lower-resolution mode with 100-m range gates. The data were continuously collected and were aggregated to hourly values of wind speed and wind direction. At the Sky Harbor Airport site, radiosondes were released on 14 days at 0800, 1000, 1200, 1400, and 1700 LST to measure profiles of potential temperatures. At the McDowell Mountain Park sites vertical profiles of potential temperature $\theta$ were measured on 11 days at 0800, 1000, 1200, and 1700 LST and on 8 days at 1400 LST. During the 1998 experimental period, winds above 2000 m were generally from the northwest or southwest at all times of the day and were associated with a series of upper-level troughs during this period (Fast et al. 2000).

The 2001 Phoenix Sunrise experiment was conducted from 10 to 30 June 2001 to obtain information on the evolving structure of the PBL during the morning transition period in Phoenix (Doran et al. 2003). Upper-air information (half-hour averages of wind data) was obtained on 16 days from 915-MHz radar wind profilers near Sky Harbor Airport (Fig. 2; site 1) and at Waddell, which is also in the vicinity of Phoenix (Fig. 2; site 3, elevation 428 m). Radiosondes were released at the Sky Harbor Airport site on 12 days at 0000, 0200, 0500, 0600, 0800, 0900, and 1000 LST. At the Waddell site,
Radiosondes were launched on 12 days at 0500, 0700, 0800, 0900, and 1000 LST. For most days of the 2001 experimental period, characteristic early-summer conditions occurred, with light winds and very low dewpoints. Data for evaluating the ability of mesoscale models to describe the evolution of the morning PBL are generally scarce, and hence there is a high value in the data from the 2001 field experiment (Doran et al. 2003).

3. Comparison of model results with observations

a. Surface temperature and winds

MM5’s performance was evaluated by means of comparing simulated 2-m air temperatures \( T_{2m} \), 10-m wind speeds \( V_{10m} \), and wind direction with data from the National Weather Service (NWS) station at Sky Harbor Airport. In MM5, \( T_{2m} \) and \( V_{10m} \) are determined diagnostically by means of the Monin–Obukhov similarity theory under consideration of the atmospheric stability from the simulated temperatures at ground level and simulated temperatures and components of horizontal wind speed at the lowest prognostic level.

The statistical measures of bias, root-mean-square error (RMSE), and standard deviation (SDE) were calculated for each hour of the day for the two simulation periods from the standard MM5 (original MRF scheme; USGS land use data) and the modified version as described in section 2b [MRF scheme according to Liu et al. (2006), updated land use data, and urban energy balance scheme (Grossman-Clarke et al. 2005)]. In the statistical calculations, observed data were subtracted from the simulated data, giving positive model biases when mean errors were positive. The results are shown for the two simulation periods 10 May–10 Jun 1998 and 10–30 June 2001 in Figs. 3 and 4, respectively.

In the simulations for 10 May–10 June 1998 with the standard MM5 version, a strong cool bias for \( T_{2m} \) at all times of the day was found that was particularly large at night (~5 K) because physical processes in the surface energy balance that contribute to the nocturnal urban heat island were not included in the model (Fig. 3). A cold bias of 2–3 K during daytime was caused by the high moisture availability and subsequent evapotranspiration for the single urban category in the standard
MM5. RMSE values were particularly high for the standard MM5 during night (up to 5 K).

The model surface temperature simulation was consistently improved when applying the modified MM5 version (Fig. 3), with the cold bias and RMSE reduced at most hours of the day to within ±1 K and ~2 K, respectively. An analysis of the influence of land use and surface energy balance characteristics on the $T_{2m}$ was presented in Grossman-Clarke et al. (2005), with the conclusion that during daytime hours the $T_{2m}$ were mostly influenced by the moisture availability for evaporation and transpiration in the urban area and also by the surrounding desert whereas nighttime temperatures were influenced highly by characteristics of the urban energy balance such as anthropogenic heating, limited sky view, and heat storage. Turbulent vertical diffusion was the dominant effect contributing to near-surface air temperatures in MM5 under typical early-summer conditions in Phoenix. Therefore, the improved results for $T_{2m}$ with the modified version of MM5 reflect the improved land use characterization as well as the physical representation of urban energy balance. On the other hand, the choice of the PBL scheme (original vs modified MRF) had no significant effect on $T_{2m}$ when land use characteristics were the same in the simulations (results not shown).

The largest bias for the modified MM5 of about 2 K occurred in the early-morning hours around 0500 LST (Fig. 3). Early-morning temperatures were overestimated by the model by up to 5 K on four days during the 1998 period. Because the Phoenix metropolitan area is situated in complex terrain under weak synoptic conditions, the diurnal pattern of the airflow consists of widespread predominantly westerly anabatic winds in the afternoon that develop in conjunction with the daily insolation. In the hours from early morning to around noon, drainage winds from the southeast, east, and north to northwest occur (Fernando et al. 2001). Using data from the 2001 Phoenix field campaign, Shaw et al. (2005) identified density currents that arrived in the Phoenix valley in the early-morning hours and that were usually a few hundred meters deep and were associated with cold advection.

On two of the four days, when the modified MM5 greatly overestimated early morning $T_{2m}$, the simulated arrival of the easterly downslope flow was delayed by several hours. For the other two days, the simulated direction of the flow never changed from westerly to a flow with an easterly component, which result was contrary to the measurements. MM5 did not capture the associated sudden drop in the measured $T_{2m}$ before sunrise on those days. Under the latter conditions, a

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**Fig. 4.** As in Fig. 3, but for the 10–30 Jun 2001 simulation period.
relatively strong westerly synoptic flow suppressed the development of the terrain-induced flow. It is common for mesoscale models not to simulate the onset of flow reversal in a timely manner (Zhong and Fast 2003; Lee et al. 2006) because the dynamic and thermodynamic effects of the complex terrain on the ambient flow and regional pressure gradients are not captured adequately. Problems might also result from motions that are not deterministically predictable because they occur on subdiurnal time scales that are not represented in the observations used to determine MM5’s initial conditions (Rife et al. 2004).

Unlike the simulated $T_{2m}$, the wind speed at 10-m height $V_{10m}$ was influenced only slightly by the land use characteristics, but rather was influenced mainly by the choice of the PBL scheme. The modified version of the MRF scheme led to a much-improved agreement between simulated and observed $V_{10m}$ during daytime (Fig. 3) in comparison with the $V_{10m}$ obtained with the original version of the MRF scheme, which were greatly underestimated, thereby confirming results by Liu et al. (2006) and Zhang and Zheng (2004). The original MRF’s behavior originated from the high values of the convective velocity that resulted in an overestimation of the friction velocity and vertical momentum transport. The slow bias of the original MRF scheme during daytime hours was reduced from up to $3 \text{ m s}^{-1}$ (RMSE $\sim 3-4 \text{ m s}^{-1}$) to less than $0.5 \text{ m s}^{-1}$ (RMSE $\sim 1-2 \text{ m s}^{-1}$), and wind speed during nighttime hours was relatively unchanged. The nighttime wind speed bias was in the range of $\pm 1 \text{ m s}^{-1}$ for both model versions. As for $T_{2m}$, the SDE values for wind speed were similar for the two model versions but were slightly larger during nighttime for the standard MM5, with values approximately between 1 and 2 m s$^{-1}$.

The modifications to the MRF scheme improved the simulation results for wind direction slightly. The bias was in the range of $\pm 50^\circ$ for both model versions. The RMSE was improved for the modified MM5 to values between 50$^\circ$ and 70$^\circ$ for the hours from 1000 LST to midnight as compared with RMSE values up to $\sim 100^\circ$ obtained with the standard MM5.

The highest RMSE values of 80$^\circ$–90$^\circ$ were calculated for the modified MM5 during the early-morning hours and were also higher than for the standard MM5 (60$^\circ$–80$^\circ$). As was discussed before, during that time of the day the direction of the airflow changed from westerly to a flow with an easterly component. The simulated change in wind direction near the surface was not always captured accurately by MM5, with a tendency to lag by several hours.

The results for the time period 10–30 June 2001 show characteristics similar to those for the 1998 period. A great improvement in the simulated $T_{2m}$ for the modified versus the standard MM5 version for most times of the day (Fig. 4) was achieved. The cold bias of the standard MM5 version was particularly large during afternoon and the evening until midnight (up to $5 \text{ K}$). With the modified MM5, the cold bias was reduced to biases of less than 2 K while the RMSE decreased from values of 4–6 K to values of 1–2 K. As for the 1998 experimental period, the largest bias of $2 \text{ K}$ occurred for the time from 0400 to 0700 LST when using the modified MM5, the main reason being the timing of the simulated shift versus the measured shift in wind direction from westerly to flow with an easterly component and the lack of the associated cold advection. SDE was similar for both model versions.

The statistical measures of bias, RMSE, and SDE for the simulation results for surface wind speeds $V_{10m}$ and wind direction for 10–30 June 2001 are given in Fig. 4. The modifications applied to MM5 greatly enhanced the model’s performance for wind speed simulation during the daytime hours. The maximum slow bias of $3 \text{ m s}^{-1}$ of the standard MM5 was reduced considerably. With daytime values of $1.5 \text{ m s}^{-1}$ for the modified MM5, the RMSE was reduced from the $3 \text{ m s}^{-1}$ of the standard MM5 version. During nighttime, the quality of the model simulations of the standard and modified MM5 versions differed only slightly. The models were in better agreement with the measurements during the first part of the night (bias $\sim 1 \text{ m s}^{-1}$ and RMSE of 1–2 m s$^{-1}$), than for the time from late afternoon to midnight for which a relatively large slow bias of up to $3 \text{ m s}^{-1}$ and an RMSE of 2–3 m s$^{-1}$ were calculated.

With values of $\pm 50^\circ$ for bias and 40$^\circ$–80$^\circ$ for RMSE and SDE for most hours of the day, the results for the wind direction simulations were similar for both the modified and standard MM5. As for the 1998 period, the deviations between simulated and measured values were largest during early-morning hours (RMSE $\sim 100^\circ$) when the change of direction in airflow that results from the location of Phoenix in complex terrain occurred.

b. Potential temperature, specific humidity, and wind profiles

The measured and simulated vertical profiles of potential temperature $\theta$ and specific humidity $q_s$ were averaged for the hours during which radiosondes were launched for the periods of 10–31 May 1998 (7 launch days) and 1–10 June 1998 (7 launch days), resulting in composite soundings for the site near Sky Harbor Airport (Fig. 2; station 1) and the rural McDowell Mountain Park site (Fig. 2; site 2). We differentiated between
the two time periods because the simulated vertical profiles of $\theta$ were generally in better agreement with the measurements for June than for May of 1998. The results are given in Figs. 5 and 6 for Sky Harbor Airport for the modified MM5 and the MM5 version using the original MRF in conjunction with 26-category land use and improved representation of the urban energy balance (called original MRF–modified LS). Also included were results for the standard MM5, to assess the successive effect of changes to the surface energy balance and land use and the PBL scheme on the simulation results.

For the 7 days of the June period (Fig. 6), the sequence of simulated composite soundings agreed to within ~1 K with the measurements at all times and heights when using the modified MM5, whereas the simulated vertical profiles of potential temperatures for the 7 days in May 1998 were on most days much cooler within the PBL than the measured profiles. Therefore the composite soundings for the May period exhibited deviations between measured and simulated values of $\theta$ of 2–3 K for all hours (Fig. 5). The deviations between the measured and simulated composites of $\theta$ near the surface were larger than the bias in $T_{2m}$ at the same hours in Fig. 3. The reason is that the data in Fig. 3 were averages of the 32 days of the 1998 period for which on many days a good agreement between measurements and simulations existed. In addition, there was a tendency for the measured $T_{2m}$ at the NWS station at Sky Harbor Airport to be lower than at the radiosonde launch site. For the radiosonde launch days in June, the “control” of the larger-scale weather as initialized and imposed through boundary conditions from the Eta model to MM5 was more accurately characterized than for most of the launch days in May. To illustrate characteristic differences in the simulations between the two time periods, $\theta$ profiles at Sky Harbor Airport as simulated by MM5 and NCEP Eta and as measured are shown in Figs. 7a and 7b for 1700 LST on 21 May 1998 and 1 June 1998, respectively. Also added to the plots were 1700 LST $\theta$ profile measurements from the nearest routine NWS radiosondes in Flagstaff and Tucson, Arizona, located 235 and 193 km away from the center of Phoenix at elevations of 2179 and 788 m, respectively. The 0500 and 1700 LST data of the latter sites were used in the Eta Model reanalysis runs. The MM5 simulations were in good agreement with the Eta Model output on both days and also agreed well with the measured $\theta$ profiles at Sky Harbor Airport for 1 June 1998 but not for 21 May 1998 on which day the simulated profiles were much cooler.

Despite the larger deviations between measured and simulated vertical profiles of $\theta$ for the seven days of the May 1998 period, the evolution of the convective PBL was reflected in the composite $\theta$ profiles obtained from the simulations with a similar quality as for the June period (Figs. 5 and 6). At around 0800 LST the measured vertical profiles of $\theta$ showed a shallow unstable layer and mixing to ~600 m, with the modified MM5 simulating mixing to heights of ~700 m. The original MRF–modified LS overpredicted mixing to heights of ~1000 m, with $\theta$ values close to the modified MM5 in the lower PBL. Because of the higher amounts of available moisture for evaporation in the urban area, the simulated $\theta$ were cooler when using the standard MM5 and less mixing occurred than with the original MRF–modified LS model.

Mixing reached to about 1200 m at 1000 LST, and by 1200 LST the mixed layer had typically grown rapidly to about 2000 m. In the early afternoon (1400 LST) the measured vertical profiles of $\theta$ showed mixing up to ~2300 m. At the three times, the results for the three model versions showed the same qualitative behavior, with a good agreement of mixing heights for the modified MM5, overestimation of mixing by the original MRF–modified LS by about 500 m, and comparatively lesser mixing when using the standard MM5. Late in the afternoon (1700 LST), the measured profiles of $\theta$ indicated further mixing to ~2500 m that was captured well by the original MRF–modified LS whereas the simulations exhibited a decline in the mixing at that time of the day to heights of ~2000 m when using the modified MM5.

The profiles of specific moisture in Figs. 5 and 6 confirm the results for vertical mixing as obtained from the $\theta$ profiles. However, the magnitude of $q_s$ was greatly overestimated by all model versions near the ground during the morning hours and was underestimated above a height of about 3000 m. The reason could be that the initial profiles from the Eta Model were too moist. Close to the surface, $q_s$ was higher for the modified MM5 than for the original MRF–modified LS, which can be attributed to mixing to higher layers in the atmosphere with the latter model version. Above the PBL the model behavior was reversed, with lower values for the modified MM5.

The radiosonde launch site near Sky Harbor Airport was located in the center of the city, and the data were therefore assumed to be representative for the convective PBL over the urban area (Fast et al. 2000). The results of the vertical profiles of $\theta$ for the rural McDowell Mountain Park site (Fig. 2: site 2) located northeast of Phoenix and adjacent to a low ridge were similar to those of the site near Sky Harbor Airport (data not shown). According to Fast et al. (2000), there was a tendency for the vertical potential temperatures to be
FIG. 5. Measured and simulated composite profiles of (top) potential temperature (K) and (bottom) specific humidity (g kg$^{-1}$) for the period of 10–31 May 1998 at Sky Harbor Airport (Fig. 2; site 1—7 radiosonde launch days for each period) at 0800, 1000, 1200, 1400, and 1700 LST. Plots represent observed (solid line), simulated using the modified MM5 (filled circles), simulated using the original MRF scheme with modified land use characteristics (solid triangles), and simulated using the standard MM5 (open triangles). Note that the vertical scale differs among panels.
FIG. 6. As in Fig. 5, but for the period of 1–10 Jun 1998.
~1 K warmer than those found at the Phoenix site in the afternoon, which was confirmed by the simulations.

The measured and simulated (for the modified MM5 and original MRF–modified LS) composite soundings (at 0500, 0600, 0800, 0900, and 1000 LST) for the period 10–30 June 2001 for the site near Sky Harbor Airport are given in Fig. 8. On 10 days, a strong stable stratification in the lowest 100–300 m of the atmosphere developed that persisted through 0600 LST followed by rapid deepening of the mixed layer after sunrise (Doran et al. 2003).

The simulated nighttime and early-morning composite vertical profiles of $\theta$ were about 1 K cooler than measured up to about 3000 m except in the first tens of meters near the ground (Fig. 8). Under conditions of very strong stability, the simulated near-surface temperature inversion at 0000, 0200, and 0500 LST was weaker than measured. This was true also for the Waddell site at 0500 LST (Fig. 2; site 3—results not shown). After sunrise, the simulated $\theta$ profiles near the surface improved (0800 LST) to a good agreement between simulated and measured data at 0900 and 1000 LST, though vertical mixing was overestimated by both versions of the MRF scheme and was more pronounced with the original MRF (Fig. 8). As for the 1998 simulations, the $\theta$ profiles obtained with the standard MM5 were much cooler than for the other two model versions (results not shown).

The absolute values of simulated composite vertical profiles of specific moisture deviated significantly from the measurements by 2–3 g kg$^{-1}$ (Fig. 8). However, the shape of the profiles indicated the same qualitative model behavior as for the profiles of $\theta$, that is, a more rapid of the breakup of the nocturnal inversion by the original MRF–modified LS scheme in comparison with the modified MM5.

The results from this study are in agreement with a comprehensive PBL scheme comparison by Zhong and Fast (2003), who showed that all of the tested schemes tended to produce weaker nocturnal inversions than were measured because of the parameterization of eddy diffusivities under stable conditions and subsequent overestimation of vertical mixing. This was also confirmed by Lee et al. (2006), who introduced to the MRF scheme a stability-dependent turbulent Prandtl number that allowed momentum to be transported by internal waves in the model, while heat diffusion was impeded by the stratification under stable conditions, thereby improving MM5’s performance for nocturnal near-surface air temperatures.

The reason for the overestimation of vertical mixing in the original MRF scheme is, in part, the formulation of the convective velocity, as discussed in section 2b. In addition, different PBL height diagnostics in the two versions of the MRF scheme led to much higher values for $h$ for the original MRF–modified LS than for the modified MM5 with larger differences than are recognizable in the vertical profiles of $\theta$. There is a positive
FIG. 8. As in Fig. 5, but for the period of 10–30 Jun 2001 (12 radiosonde launch days) for 0500, 0600, 0800, 0900, and 1000 LST. Plots represent observed (solid line), simulated using the modified MM5 (filled circles), and simulated using the original MRF scheme with modified land use characteristics (solid triangles).
feedback of $h$ on the vertical mixing through the profile function used to calculate diffusivity coefficients (Hong and Pan 1996), which further intensifies vertical mixing in the original MRF.

The evolution of the composite measured and simulated PBL heights between 10 May and 10 June 1998 and between 10 and 30 June 2001 are shown in Figs. 9a and 10a, respectively, for Sky Harbor Airport, as well as for the rural McDowell Mountain Park (Fig. 9b) and Waddell site (Fig. 10b).

Under convective conditions the measured PBL heights were obtained by means of two methods: the bulk Richardson method (Seibert et al. 2000) and by subjectively evaluating the profile measurements of potential temperature. In the latter case, the measured PBL height was assumed to be at one-half of the depth of the elevated inversion or stable layer, as suggested by Stull (1988). Both methods yielded similar PBL heights, with the Rib method giving higher values for the late afternoon for days on which the elevated inversion was not very pronounced. When mechanical turbulence production was significant, two different regions of the vertical $\theta$ profile could be distinguished near the ground: a layer with a strong nearly linear increase of the potential temperature followed by a layer with a weaker decrease in $\theta$ as a result of exclusively radiative cooling. The PBL height was assumed to be at the usually sharp transition between the two layers (Seibert et al. 1998). The simulated PBL heights were calculated as described in section 2b.

Even though mixing was still overestimated with the modified MM5 in the early-morning hours, a much better agreement between simulated and measured PBL heights was achieved than with the original MRF–modified LS for the morning and early afternoon for both years and all sites. However, because of the diag-
nostic methods for the determination of PBL heights, 
the differences in $h$ as simulated with the two MRF 
schemes were larger than the $\theta$ profiles indicated. The 
values for the standard MM5 fell between the results of 
the other two model versions (Figs. 9a,b). Because of 
the decrease in vertical mixing at around 1600 LST, the 
modified MM5 underestimated the PBL heights late in 
the afternoon at 1700 LST (Figs. 9a,b). The results for 
the rural sites as obtained with the two PBL schemes 
were in qualitative agreement with the launch site in 
the urban area.

For the 1998 period, the simulations gave, on average, slightly ($\sim 100$ m) higher maximum values of the 
simulated PBL height for the urban site in comparison 
with the rural McDowell Mountain site. According 
to the measurements and simulations of the 2001 period, 
the urban PBL at Sky Harbor Airport developed 
slightly faster between 0700 and 0900 LST in comparison 
with the rural Waddell site and was about 200 m 
higher from 1400 to 1600 LST.

The results are in agreement with Liu et al. (2006) for 
Oklahoma City, for which the PBL height calculated 
with the original MRF approach developed too early 
and became too deep during the daytime. The modified 
MRF scheme led to a consistent improvement in the 
simulation of the convective PBL at all times of the day 
except in the late afternoon, when vertical mixing was 
underpredicted.

To evaluate MM5’s performance for the observed 
wind speeds and flow pattern, the measured and simu-
lated wind profiles for the 1998 and 2001 experimental 
periods were averaged for undisturbed days (weak syn-
optic conditions) for the site near Sky Harbor Airport 
to obtain composite wind profiles. The profiler data 
depicted that the typical flow pattern developed on 27 
of the 33 days of the 1998 field experiment and on 13 
days of the 16 days of the 2001 Phoenix Sunrise exper-
iment. The westerly winds, when fully developed, had 
wind speeds of $\sim 5$ m s$^{-1}$ in the lowest 1–2 km of the 
atmosphere and reached the synoptic-scale flow. For 
the 2001 period, the predominantly westerly flow oc-
curred on average earlier in the day ($\sim 1200$ LST) than 
during the 1998 experimental period ($\sim 1700$ LST). The 
easterly flow developed after midnight, extending to a 
maximum depth of about 1–1.5 km above ground, and 
was on most days more pronounced during the 2001 
experimental period in comparison with the 1998 ex-
perimental period in terms of wind direction and wind 
speed. For both years there was a tendency for the 
simulated onset of the easterly and westerly flow to be 
delayed by several hours and to affect deeper layers in 
the atmosphere earlier than was measured, with no 
consistent differences between the results for the two 
versions of the MRF scheme.

The 1998 vertical profiles of measured and simulated 
(with three model versions: standard MM5, modified 
MM5, and original MRF–modified LS) composite wind 
speeds for 0800, 1000, 1200, 1400, and 1700 LST are 
given in Fig. 11. Sodar data were available for the 1998 
experimental period that provided measurements of 
wind speed for the lowest $\sim 100$ m in the atmosphere 
and were included as insets in the graphs of Fig. 11 for 
each hour. In the early-morning hours, winds deviated 
only slightly among the three model versions. For most 
daytime hours, the PBL winds were underpredicted by 
the standard MM5 except for a minimum in wind speed 
at about 700 m. The modifications to the surface energy 
balance and land use improved the representation of 
the PBL winds with both the modified MM5 and the 
original MRF–modified LS. However, as is recogniz-
able from the comparison with the sodar data, the origi-
nal MRF–modified LS model considerably underesti-
mated near-surface winds for 1000, 1200, and 1400 LST 
(which was also true for other daytime hours; results 
not shown) whereas the agreement was good for the 
modified MM5. Those results confirm the simulations 
for surface winds as discussed in section 3a. There were 
no sodar data available for the 2001 period, but the 
behavior for PBL winds was qualitatively similar to that 
for the 1998 period (results not shown).

4. Conclusions

In this study, a version of MM5 was applied that 
included a refined land cover classification and updated 
land use/cover data for the arid Phoenix metropolitan 
area, as well as bulk approaches of characteristics of the 
urban surface energy balance, while PBL processes 
were simulated by a modified version of the MRF 
scheme. The results of the study show a consistently 
Improved model performance for near-surface and up-
per-air temperatures and wind speeds when applying 
the modified MM5. In particular, a cold bias in $T_{2m}$ and 
$\theta$ in the standard MM5 during day and nighttime hours 
was reduced at all times of the day because of the improved 
land use characterization and physical representation 
of the urban energy balance. An analysis of the 
influence of land use and surface energy balance char-
acteristics on the simulated $T_{2m}$ and $V_{10m}$ (Grossman-
Clarke et al. 2005) showed that, during daytime hours, 
the $T_{2m}$ were mostly influenced by the moisture avail-
ability for evapotranspiration in the urban area and also 
by the surrounding desert, whereas nighttime tempera-
tures were influenced highly by characteristics of the 
urban energy balance (anthropogenic heating, limited
sky view, and heat storage). Those results were confirmed in this study by the vertical profiles of $\theta$ that showed a close agreement for the two MRF schemes in the lower PBL when surface characteristics were the same but deviations in the upper PBL that are due to the more vigorous mixing for the original MRF. The modified MRF scheme described vertical mixing more accurately than the original MRF scheme except during the late afternoon, when mixing was underpredicted.

Near-surface wind speeds were influenced mainly by the choice of the PBL scheme, with a much-improved agreement between simulated and observed $V_{10m}$ during daytime for the modified MRF in comparison with the original MRF scheme. The modifications to the surface characteristics improved the representation of the PBL winds for both versions of the MRF scheme, whereas the PBL winds were underpredicted by the standard MM5 during daytime.

There is a possibility that errors in surface flux simulations compensate or exaggerate deficits in the PBL schemes. Surface flux data were not available from the two field campaigns, and further analysis is necessary to evaluate the quality of the model simulations with respect to the components of the surface energy balance. As was shown in Grossman-Clarke et al. (2005) under the weak synoptic conditions that were dominant during the two field experiments in Phoenix, the surface $T_{2m}$ are strongly influenced by vertical mixing and therefore surface sensible heat fluxes. The improved simulations for $T_{2m}$ indirectly support the quality of the surface flux simulations. Furthermore the results of this study support results from previous studies by Zhong and Fast (2003), Zhang and Zheng (2004), and Liu et al. (2006).

The analysis of differences between the urban and rural PBL in the region was complicated by the influ-
ence of complex terrain on the airflow, and only slight differences between the simulated urban and rural PBL were detected. Therefore, to study the urban effect, we conducted additional case studies for which the urban thermodynamic and dynamic effects were removed from the simulations and were displaced by physical characteristics of the desert land use category. The results indicated that, because of the special urban properties, the urban effect on the PBL in the arid Phoenix metropolitan area differs from that found in cities in midlatitude environments. For the latter, the urban PBL is characterized by greatly enhanced mixing in comparison with the rural PBL, resulting from large surface roughness and increased surface heating (Fisher et al. 2005), whereas according to the simulations for Phoenix the urban PBL is slightly lower during afternoon hours than it would be for desert land use because of irrigated landscaping and subsequent enhanced evapotranspiration in the urban areas versus the natural desert areas. Mesoscale meteorological model simulations for cities in midlatitude environments showed that that the deeper and drier urban PBLs caused low-level convergence that is favorable for producing deep precipitating cumulus clouds downwind of the city (Cotton and Pielke 1995; Bornstein and Lin 2000; Rozoff et al. 2003; Burian and Shepherd 2005). Therefore, the Phoenix metropolitan area might potentially influence precipitation differently than cities located in humid midlatitude environments. Combining historical and remote sensing–based precipitation data, Diem and Brown (2003) and Shepherd (2006) showed a statistically significant increase in mean precipitation of 12%–14% from the preurban to the posturban period for locations in northeastern suburbs of Phoenix. The authors assume that in this region the outflow boundaries from storms can most effectively interact with the convergence and flux forcing on the edge of the city. To study mechanisms by which Phoenix might potentially influence monsoon convective activity using mesoscale meteorological models, it is necessary to resolve the evolution of the urban PBL and the resulting thermal mesoscale circulations that interact with the thunderstorm outflow propagating from the elevated terrain to the northeast and north (Bright and Mullen 2002). A comprehensively tested mesoscale model in terms of the evolution of the urban PBL is a significant step in enabling the investigation of those individual contributions of dynamic forcing mechanisms that potentially affect precipitation.

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