An Observational and Modeling Study of Characteristics of Urban Heat Island and Boundary Layer Structures in Beijing

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ABSTRACT

In this paper, the characteristics of urban heat island (UHI) and boundary layer structures in the Beijing area, China, are analyzed using conventional and Moderate Resolution Imaging Spectroradiometer (MODIS) observations. The Weather Research and Forecasting (WRF) model coupled with a single-layer urban canopy model (UCM) is used to simulate these urban weather features for comparison with observations. WRF is also used to test the sensitivity of model simulations to different urban land use scenarios and urban building structures to investigate the impacts of urbanization on surface weather and boundary layer structures. Results show that the coupled WRF/Noah/UCM modeling system seems to be able to reproduce the following observed features reasonably well: 1) the diurnal variation of UHI intensity; 2) the spatial distribution of UHI in Beijing; 3) the diurnal variation of wind speed and direction, and interactions between mountain–valley circulations and UHI; 4) small-scale boundary layer convective rolls and cells; and 5) the nocturnal boundary layer lower-level jet. The statistical analyses reveal that urban canopy variables (e.g., temperature, wind speed) from WRF/Noah/UCM compare better with surface observations than the conventional variables (e.g., 2-m temperature, 10-m wind speed). Both observations and the model show that the airflow over Beijing is dominated by mountain–valley flows that are modified by urban–rural circulations. Sensitivity tests imply that the presence or absence of urban surfaces significantly impacts the formation of horizontal convective rolls (HCRs), and the details in urban structures seem to have less pronounced but not negligible effects on HCRs.

1. Introduction

Urbanization rapidly spreads all over the world, and markedly modifies local and regional atmospheric properties, especially planetary boundary layer (PBL) structure, by perturbing the wind, temperature, moisture, turbulence, and surface energy budget fields. The well-recognized urban heat island (UHI) phenomenon, characterized by a temperature contrast between a city and its surrounding rural areas, is one prominent urban effect and can affect urban airflow, atmospheric boundary layer structures, and transport and dispersion of pollutants. Bornstein (1968, 1987) observed this phenomenon, which typically occurs under clear skies with weak ambient wind conditions at night, but may occur during daytime as well. An urban cool island is an urban area that is cooler than its surrounding rural areas. Oke (1995) presented a comprehensive review of earlier observational studies on the characteristics, causes, and effects of UHI. Grimmond (2006) and Souch and Grimmond (2006) reviewed recent large campaign-style urban climate studies [e.g., the French Urban Boundary Layer/Couche Limite Urbaine–Field Experiment to
Constrain Models of Atmospheric Pollution and Emissions Transport (UBL/CLU-ESCOMPTE; Mestayer et al. 2005), the Basel Urban Boundary Layer Experiment (BUBBLE; Rotach et al. 2005), and the Joint Urban 2003 campaign (Allwine and Flaherty 2006). These works have significantly advanced the recognition of spatial differences both within and between cities as a result of differences in urban fabric (materials, morphology), emissions, and prevailing meteorological and climatic conditions.

The Greater Beijing metropolitan area, China, one of the 10 largest megacities in the world with a population of more than 10 million, has experienced a rapid urbanization in the last 20 years. Such urban expansion, with increasing built-up areas and human activities, results in significant modifications in the underlying surface properties and atmospheric circulations. Ren et al. (2007) investigated the temperature change using observations from downtown Beijing and its nearby rural stations and found that annual and seasonal urbanization-induced warming for 1961–2000 in Beijing was generally significant. Li and Shu (2008) analyzed the impacts of Beijing city on the boundary layer nocturnal low-level jet (LLJ) using tethersonde data and showed that the LLJ over urban areas appeared at higher vertical levels than that over suburban sites. Numerical simulations by Guo et al. (2006) revealed that the urban region could act to create a bifurcation zone for precipitation distribution and produce more floods. Zhang et al. (2009) investigated the impacts of urbanization and future green planting on summer precipitation in the Greater Beijing metropolitan area using a mesoscale model with the bulk roughness approach to account for the urban impacts. However, because of limited observations, the UHI and boundary layer structure in Beijing have not been systematically investigated.

On the other hand, significant progress has been made in the last decade to model the urban surface (Masson 2006; Souch and Grimmond 2006). Generally, there are three approaches to account for urban effects in mesoscale meteorological models, which include the bulk roughness approach (e.g., Liu et al. 2006), the one-layer urban canopy model (UCM) (e.g., Masson 2000; Kusaka et al. 2001), and the multilayer UCM (e.g., Martilli et al. 2002; Dupont et al. 2004). In the recent release of the community mesoscale Weather Research and Forecasting (WRF) Model, version 2.2, the single-layer UCM (Kusaka et al. 2001) was coupled to the “Noah” land surface model (Chen and Dudhia 2001). This single-layer UCM is in the middle of the spectrum of urban modeling methods, and is a compromise between urban model complexity and computational resources required to execute urban models. It takes the urban building geometry into account in its surface energy budgets and wind shear calculations. Radiative, thermal, and moisture effects and canopy flow model are accounted for. This coupled mesoscale atmospheric–urban modeling system enables us to study urban effects.

In this paper, we combine observations and the coupled WRF/Noah/UCM model to focus on the diurnal evolution of the UHI and PBL structure in the Beijing
area and on the complex interactions between mountain-valley winds induced by nearby mountains and the UHI circulation for an anticyclone condition. Our overall objectives in this study are to 1) describe the general characteristics of urban heat island and PBL structures in the Beijing area, 2) understand the degree to which the new-generation numerical weather prediction (NWP) model, the WRF Model, can capture these physical mechanisms, and 3) understand the impacts of urbanization on PBL properties. In section 2, we use observations to examine the boundary layer structure over Beijing. We describe, in section 3, the WRF/Noah/UCM model and the use of it to simulate observed surface weather variables and PBL structures in the Beijing urban areas. Section 4 discusses various sensitivity tests, followed by a summary in section 5.

2. Observed PBL structures for a summer clear day in Beijing

   a. Terrain and surface observation stations

   The distribution of complex terrain in the vicinity of Beijing is shown in Fig. 1, with high mountains to west and north of Beijing city. The west mountains are closer...
to Beijing than the north mountains. The maximum terrain height is about 2000 m, and the distance from 2000-m high mountains to downtown Beijing (about at sea level) is about 100 km. Such steep variation of terrain heights often results in mountain–valley flows.

Figure 2 shows the location of 60 surface observation stations (equipped with the automatic weather station MAWS301 by Vaisala, Inc., Finland) located over different land use types and a wind profiler (Airda 3000A; Weng et al. 2001) located in Baolian between the third beltway and the fourth beltway of Beijing. With the same land-cover classification as in 2001 national land cover data (NLCD; Yang et al. 2003), we use local survey data to categorize Beijing urban land use by impervious surface percentage: open space <20%, low density 20%–49%, medium density 50%–79%, and high density 80%–100%. The majority of stations is located in high-density urban areas.

b. Synoptic weather condition of a summer case

Because it is easier to discern urban effects during clear days with weak synoptic forcing, a summer clear day is chosen to carry out this study. Figure 3 shows the synoptic weather pattern at 0000 UTC (0800 LST) and 1200 UTC (2000 LST) 18 August 2005 and 0000 UTC (0800 LST) 19 August 2005 at 850 hPa. A high pressure system lies over the Beijing area and slowly moves toward the east. Beijing is in the center of the high throughout this period with slight variations of geopotential height and temperature, and with weak synoptic wind.

c. UHI intensity

The UHI intensity is defined as the mean air temperature difference between stations inside (as urban areas) and outside of the fourth beltway (as rural areas). The monthly mean UHI intensity for August 2005 is below 0.5°C from 0000 to 1000 UTC (0800–1800 LST) with the minimum of 0.05°C at 0200 UTC (1000 LST) (Fig. 4). From 1100 UTC (1900 LST), around sunset, it grows rapidly and reaches a maximum of 1.12°C at 1300 UTC (2100 LST). The UHI intensity declines slightly through the rest of the night and is rapidly eroded after sunrise. The intensity averaged
for 14 no-rain days in August 2005 has diurnal variations similar to the monthly mean, but is much stronger, especially in nighttime with a maximum of 1.62°C. The UHI intensity for 18 August 2005 is −0.35°C at 0100 UTC (0900 LST); that is, the temperature in the city is lower than that in the surrounding rural area. This type of urban “cool” island in the morning time was observed in other studies (Oke 1982; Bornstein 1987), probably as a result of advection of warmer air to rural areas. In addition at this time of day, urban aerosols may be the main influence on radiation processes, reducing solar radiation into the city. The second minimum (0.4°C) appears at 1000 UTC (1800 LST), the same time as in monthly mean intensity. The daily maximum is 2.4°C at 1500 UTC (2300 LST). The UHI intensity between Station 203 in a high-density urban area and rural stations in Fig. 4 shows that the cool island has persisted for several hours from the morning to noon with the minimum of −1.59°C, while the maximum of UHI intensity is 5.34°C at 1300 UTC (2100 LST). During the day, the UHI intensities for the monthly mean, no-rain-day mean, and 18 August are similar except for the 2-h urban cool island on 18 August. The largest day-to-day differences appear at night, which may be caused by frequent summer nighttime thunderstorm activity.

d. Horizontal distribution of land surface temperature and wind fields

The Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature–emissivity 5-min product in version 4 (Wan et al. 2002) is used in this
study. These data can be freely obtained online (http://lpdaac.usgs.gov). Figure 5 depicts the spatial distribution of land surface temperature for the domain shown in Fig. 2, based on 1-km-resolution MODIS data valid at 0445 UTC (1245 LST) and 1825 UTC 18 August 2005 (0225 LST 19 August 2005), respectively. There is distinct UHI for land surface temperature at noon and nighttime, and its intensity is about 6°C at noon and about 3°C at night. Hence the noon UHI land surface temperature pattern is stronger than nighttime from this particular case. Note that this is different from the UHI of 2-m air temperature.

The diurnal variation of the observed 10-m wind field is shown in Fig. 6. In the morning (0800 LST 18 August 2005), there is northeasterly wind, which seems to be both synoptic and mountain wind from the northern mountains to downtown Beijing. At 1400 LST, the wind turns easterly and northeasterly (i.e., upslope wind toward the western mountains). In the downwind urban areas (e.g., south part of second to fifth beltway), the wind speed is much reduced, largely due to rougher surfaces in urban areas, which seem to form a confluence zone and may favor accumulation and lofting of air pollutants. Because these convergence zones appear mostly in downtown areas, they are most likely induced by urban circulations (Shreffler 1978). At 2000 LST, the wind turns to westerly (i.e., downslope from the western mountains). Later at 0200 LST, the wind turns to northerly, dominated by downslope wind from the northern mountains. Again, convergence zones form in

### Table 1

<table>
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<tr>
<th>Land use</th>
<th>N_stn</th>
<th>Mean Obs</th>
<th>Mean T2</th>
<th>Mean TC</th>
<th>Std dev Mean</th>
<th>Std dev T2</th>
<th>Std dev TC</th>
<th>Mean bias Mean</th>
<th>RMSE Mean</th>
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<th>IOA T2</th>
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<tr>
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<td>23.81</td>
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<td>0.93</td>
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<td>0.63</td>
<td>0.93</td>
<td>0.93</td>
<td>0.63</td>
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<tr>
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<td>0.86</td>
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<td>0.95</td>
<td>0.70</td>
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the downtown areas. At 0800 LST (not shown), there is strong northerly downslope wind from the northern mountains. Therefore, the local circulation in the Beijing area is dominated by mountain–valley wind, and yet presumably modulated by UHI circulations.

e. Diurnal variation of the wind and PBL height from wind profiler observation

Miao and Chen (2008) analyzed the diurnal variation of wind and PBL height from the wind profiler at Baolian located between the third beltway and the fourth beltway in downtown Beijing and found that from 0300 UTC (1100 LST) 18 August 2005, strong updraft–downdraft couplets appear, accompanying strong variations in PBL height. Presumably, the observed daytime variation of wind and PBL height is related to horizontal convective rolls (HCRs), which their model runs showed to be the main form of convection in the urban area.

3. WRF/Noah/UCM numerical simulations

a. WRF/Noah/UCM modeling system

The WRF Model is a nonhydrostatic, compressible model with a mass coordinate system. We integrate the Advanced Research WRF (ARW version 2) described by Skamarock et al. (2005) over the five nested domains shown in Fig. 7. The grid spacing (grid numbers) of these five domains is 40.5 km (100 × 100), 13.5 km (100 × 100), 4.5 km (100 × 100), 1.5 km (100 × 100), and 0.5 km (118 × 109), respectively. The vertical grid contains 38 full sigma levels from the surface to 50 hPa, of which the lowest 13 levels are below 1 km so as to have finer resolution in the PBL. A 24-h simulation (0000 UTC 18 August–0000 UTC 19 August 2005) is conducted with the initial and boundary conditions from the National Centers for Environmental Prediction (NCEP) operational Global Final (FNL) Analyses on a 1.0° × 1.0° grid. We use the Mellor–Yamada–Janjić PBL scheme (Janjić 1990, 1994), which predicts turbulent kinetic energy and allows vertical mixing between individual layers within the PBL. Other physical parameterizations include the WRF single-moment six-class graupel scheme, the shortwave radiation schemes (Dudhia 1989), the Rapid Radiative Transfer Model longwave radiation scheme, and the Noah land surface model (LSM) (Chen and Dudhia 2001; Ek et al. 2003).

The Noah LSM provides surface sensible and latent heat fluxes, and surface skin temperature as lower boundary conditions to WRF. To represent the thermal and dynamic effects of urban areas, the single-layer urban canopy model of Kusaka et al. (2001) and Kusaka and Kimura (2004) was coupled to Noah. The basic function of a UCM is to take urban geometry into account in its surface energy budgets and wind shear.

TABLE 2. Comparison of the simulated and observed 10-m wind speed (m s⁻¹; the criterion for hit rate calculation is 1 m s⁻¹). U10: 10-m wind speed; UC: wind speed in urban canopy.

<table>
<thead>
<tr>
<th>Land use</th>
<th>N_stn</th>
<th>Obs</th>
<th>U10</th>
<th>UC</th>
<th>Mean</th>
<th>Std dev</th>
<th>Mean bias</th>
<th>RMSE</th>
<th>IOA</th>
<th>HR</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1.12</td>
<td>2.06</td>
<td>—</td>
<td>0.72</td>
<td>0.86</td>
<td>—</td>
<td>0.95</td>
<td>1.46</td>
<td>0.43</td>
</tr>
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<td>2.21</td>
<td>—</td>
<td>0.82</td>
<td>0.91</td>
<td>—</td>
<td>1.38</td>
<td>1.87</td>
<td>0.32</td>
</tr>
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<td>0.42</td>
<td>0.66</td>
<td>0.71</td>
<td>0.18</td>
<td>0.39</td>
<td>-0.27</td>
<td>0.56</td>
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<tr>
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<td>0.20</td>
<td>0.30</td>
<td>-0.47</td>
<td>1.10</td>
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</table>

TABLE 3. Comparison of the simulated and observed 2-m specific humidity (g kg⁻¹; the criterion for hit rate calculation is 2 g kg⁻¹). Q2: 2-m specific humidity; QC: specific humidity in urban canopy.

<table>
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<th>Land use</th>
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<th>Q2</th>
<th>QC</th>
<th>Mean</th>
<th>Std dev</th>
<th>Mean bias</th>
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<th>IOA</th>
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<td>QC</td>
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<td>High density</td>
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<td>1.77</td>
<td>-1.61</td>
<td>-1.57</td>
<td>2.19</td>
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</table>
FIG. 10. As in Fig. 5, but for WRF results.

FIG. 11. The simulated (blue vectors) and observed (red vectors) wind fields at the height of 10-m AGL in D05: (a) 0600 UTC (1400 LST), (b) 1200 UTC (2000 LST), (c) 1800 UTC 18 Aug 2005 (0200 LST), and (d) 0000 UTC (0800 LST) 19 Aug 2005.
calculations. This WRF/Noah/UCM coupled modeling system (Chen et al. 2004, 2006) includes 1) 2D street canyons that are parameterized to represent the effects of urban geometry on urban canyon heat distribution; 2) shadowing from buildings and reflection of radiation in the canopy layer; 3) canyon orientation and diurnal cycle of solar azimuth angle; 4) a manmade surface consisting of eight canyons with different orientation; 5) Inoue’s model for canopy flows; 6) a multilayer heat equation for roof, wall, and road interior temperatures; and 7) a very thin bucket model for evaporation and runoff from road surfaces. Two further improvements are made to UCM. One is the calculation of wind speed within the urban canopy, and the other is the ingesting of anthropogenic heat associated with energy consumption by human activities.

Replacing the urban canopy element drag term in Eq. (A22) of Kusaka and Kimura (2004), \(-\gamma_c c_d a_z U|U|\), by the expression of Coceal and Belcher (2005), \(-\gamma_n (#/z_r) U|U|\), we can get \( U = U_r \exp\{n[(#/z_r) - 1]\} \). Here, \( n = z_r (#/z_r 2l^2)^{1/3} \), \( \gamma_n \) is the effective fluid volume, \( c_d \) is a drag coefficient, \( a_z \) is a function of height and is equal to the surface area of the buildings per unit volume of air, \( \lambda_f \) is the total frontal area per unit ground area, \( z_r \) is the mean building height, \( U_r \) is wind speed at the height of \( z_r \), and \( l \) is the mixing length. This method avoids introducing a constant \( c_d \) in the calculation of wind speed in the urban canopy—an advantage because this constant has not been determined very well (Brown 2000).

There are two methods to account for anthropogenic heat sources in meteorological models: adding it to the energy balance at the surface (Ichinose et al. 1999) or adding it to the first level of the model (Taha 1999). In our attempt to represent it more realistically, half of the anthropogenic heat from buildings \((Q_B)\) and vehicles \((Q_V)\), \((Q_B + Q_V)/2\) is added to the energy equation at the first vertical level above the ground and the other half to the surface energy equations of roofs, walls, and roads.

High-resolution land use, land cover, building morphology, and statistical energy consumption data for Beijing are used to derive urban parameters for the UCM, adopting methods similar to those of Burian et al. (2002) and Sailor and Lu (2004). The diurnal variation of vehicular traffic is considered according to some typical traffic flux observations in Beijing (e.g., Chen et al. 2005). Figure 8 depicts the distribution of sky view factor (SVF; Sakakibara 1996) and total anthropogenic heat, \((Q_B + Q_V)\), at 0800 LST for the WRF fifth domain with a grid spacing of 500 m. High and dense buildings with relatively narrow roads located between the second beltway and the fifth beltway result in small SVF. The maximum total anthropogenic heat in a summer morning during the peak traffic time is more than 200 W m\(^{-2}\).
b. Analyses and verification of simulation results

Figure 9 shows that the WRF model well simulated the general synoptic weather pattern and in particular the geopotential height pattern and temperature distribution at 1200 UTC (2000 LST) 18 August 2005 and 0000 UTC (0800 LST) 19 August 2005 at 850 hPa, except the fields in the Tibetan Plateau look different.

The verification statistics of 2-m temperature, 10-m wind speed, and 2-m specific humidity for the entire time period are shown in Tables 1–3. Index of agreement (IOA; Pielke and Pearce 1994), hit rate (HR; Schlu¨ nzen and Katzfey 2003), and other statistics are calculated. The hit rate is a reliable overall measure for describing model performance, because it is able to consider the measurement uncertainty, which is difficult to consider in the bias or the root-mean-square error (RMSE). The criteria for hit rate calculation are for model–observation agreement within 2°C for 2-m temperatures, 1 m s⁻¹ for wind speed, and 2 g kg⁻¹ for 2-m specific humidity (Cox et al. 1998).

The urban canopy temperatures from WRF/Noah/UCM (TC in Table 1) averaged over low-, medium-, and high-density urban areas are lower than the corresponding 2-m temperature (T2) averaged for these urban land use categories, but closer to observations. However, T2 averaged over open-space urban areas is higher than TC, and closer to observations. This is due to the lower buildings and shallower urban canopy in open-space urban areas. The best agreements are found for high-density urban areas; hence dramatic urban characteristics appear to be relatively easier to model. The hit rate for TC (0.78) is higher than that for T2 (0.70). Therefore, in urban areas TC appears to compare with observations better than T2. Note that TC and UC are air temperature and wind speed in urban canopy approximately at half the mean building height ranging from 0.5 to 10 m.

In Table 2, the mean urban canopy wind speed (UC) is about 0.5 m s⁻¹ lower than 10-m wind speed (U10). HR of UC (0.75) averaged for all surface stations is higher than that of U10 (0.62). The mean of simulated wind speed from WRF (1.25 m s⁻¹) is larger than the observed mean (0.98 m s⁻¹). Furthermore, the simulated wind speeds over croplands and pastures (2.06 m s⁻¹) and over mixed forests (2.21 m s⁻¹) are larger than the observations (1.12 and 0.82 m s⁻¹). Because these areas may have been partly urbanized, the outdated local land use data are presumably responsible for this discrepancy. The urban canopy specific humidity (QC) is close to the 2-m specific humidity (Q2), and HR for QC (0.61) is slightly higher than that for Q2 (0.60). The mean biases and root-mean-square errors in Tables 1–3 are all in reasonable and acceptable ranges.

The weighted hit rates of this case, calculated by weighting the single hit rates with the number of comparison data, are 0.65 and 0.73 for conventional variables and urban canopy variables, respectively. In summary, these statistics suggest that the WRF/Noah/UCM modeling system simulates this case generally well, and using the diagnosed variables within urban canyon produces better agreement with observations than conventional 2- and 10-m variables. The vertical distribution of variables in urban canopy is different from that over the natural landscape, so the diagnostic formulas based on traditional Monin–Obukhov similarity theory for 2- and 10-m variables are not applicable in urban areas. For instance, the wind distribution in the urban canyon is assumed to be exponential. This is
presumably responsible for the better agreement between canopy variables and observations than 2- and 10-m derived variables.

The simulated UHI intensity for 18 August 2005 from the WRF Model, when compared with observations in Fig. 4, did not capture the urban cool island between 0100 and 0200 UTC. The daytime simulated UHI intensity is much stronger, and has a dip at 0900 UTC (1700 LST), 1 h earlier than observed. The second minimum of UHI intensity around sunset (1700–1800 LST) appears in all the lines in Fig. 4, which is due to a slightly larger cooling rate in urban areas in the afternoon and smaller cooling at night (air temperature in urban area is shown in Fig. 12). The maximum of 2.9°C appears at 1400 UTC (2200 LST), being 0.5°C higher and 1 h earlier than the observed value. The cool bias of simulated 2-m air temperatures at rural sites (shown in Table 1) is responsible for the disagreement between observed and simulated UHI intensity.

Figure 10 gives the spatial distribution of simulated land surface temperature departures from the domain mean valid at 0445 UTC (1245 LST) and 1825 UTC (0225 LST 19 August 2005). Compared with Fig. 5, the WRF/Noah/UCM model simulates the spatial extent of UHI and location of maximum UHI reasonably well. Nevertheless, the simulated nighttime land surface temperature UHI are about 3°C higher than MODIS observations.

The simulated surface wind fields in Fig. 11 show upslope wind toward the western mountains at 1400 LST with convergence zones in and downwind of the urban area (southwest part of downtown Beijing), and downslope wind from the western mountains at 2000 LST. At 0200 LST, the wind flows downslope from the northern mountains, and produces convergence in urban areas. Therefore, comparing to observed winds in Fig. 6, the model successfully captures the wind distribution and diurnal variation. The local circulation is dominated by mountain valley wind, and is presumably affected by UHI circulation.

Figure 12 shows the diurnal variation of the observed and simulated 2-m temperature, surface temperatures, 10-m wind speed, and 2-m specific humidity averaged over high-density urban area stations, and they match very well. Among the urban surface temperatures, the urban ground surface temperature has the largest diurnal amplitude, while the wall surface temperature has the smallest diurnal range, reflecting the difference in thermal conductivity and heat capacity. Urban canyon temperature and wind speed are lower than their counterparts at 2 and 10 m. The model successfully captures the diurnal variation of 2-m specific humidity.

Miao and Chen (2008) revealed that the diurnal variation of simulated vertical velocity, horizontal wind vectors, and PBL height agrees generally well with the
observations from the Baolian wind profiler. They also analyzed the distribution of the wind and $-z/L$ ($z$ is the convective boundary layer depth and $L$ is the Monin–Obukhov length) and found that in the afternoon the HCRs formed in urban areas with axes oriented along the wind. The occurrence of HCRs in urban areas is generally confined in the areas with $-z/L < 25$, consistent with previous field observations of HCRs over natural landscapes (Weckwerth et al. 1999). They also showed that there are more cells in rural regions and more rolls in urban areas because of different land surface properties and boundary layer instability conditions.

Two cross sections AB and CD (their position is marked in Fig. 8a) are selected to examine the vertical distribution of wind normal to these cross sections: AB being perpendicular to the average wind at 2100 LST.

![Fig. 15. The diurnal variation of the difference between (left) the two sensitivity cases and (right) the control case averaged over the dashed rectangle area in Fig. 8a: (a),(b) temperature ($^\circ$C), (c),(d) wind speed (m s$^{-1}$), and (e),(f) specific humidity (g kg$^{-1}$).]
and CD perpendicular to average wind at 0200 LST. As shown in the $u$ component at 2100 LST in Fig. 13a, the LLJ is in the early formation stage. The LLJ can be seen in the boundary layer over rural areas at 39.7°–39.8° N, but it is largely absent over urban areas. The LLJ is stronger at 0200 LST, shown in the $v$ component in Fig. 13b, and appears over urban areas with weaker intensity and thinner extension, and is located higher from the ground in the boundary layer than that over rural areas, which is consistent with the observational analyses using tethersonde data (Li and Shu 2008). Liu et al. (2006) found similar behavior. The lower LLJ speed over the city is presumably because of both the larger roughness elements and the slightly more unstable surface layer there.

4. Impacts of urbanization on surface weather variables and boundary layer structures

In this section, we utilize the WRF/Noah/UCM modeling system to conduct several sensitivity experiments by changing the inner domain land use or urban properties to examine the urbanization effects on the boundary layer structure in the Beijing area. In the first sensitivity test (referred to as U2C), all urban land use grid points in domain 5 in the control experiment (described in section 3, referred to as CTRL) are replaced by dry cropland (U.S. Geological Survey category 2). In the second sensitivity test (referred to as FU), all grid points except the water body in the domain within the dashed rectangle of Fig. 8a are converted into high-density land use (using the default urban parameters in the table of WRF/Noah/UCM with building height of 10 m). Retaining the same land use distribution as in CTRL but changing urban parameters in UCM, we conduct four additional tests with half the building heights, double the building heights, half the anthropogenic heat, and double the anthropogenic heat, respectively. All these sensitivity experiments are conducted using initial conditions and physics schemes identical to the CTRL simulation.

Figure 14 shows the diurnal variation of some components of surface energy balance from three cases averaged over the dashed rectangle area in Fig. 8a. Because of complex buildings, the urban surface increases trapped shortwave radiation and heat storage, especially at
local solar noon when the downward shortwave radiation reaches its maximum. At night, the urban area releases more heat from ground to the air, which is well simulated in case FU. Sensible (latent) heat flux in case FU is larger (smaller) than that in the CTRL case. However, net shortwave flux, sensible heat flux, and ground heat flux (latent heat flux) in case U2C are smaller (larger) than those in the CTRL case.

Diurnal variations of the differences between the two sensitivity cases and the control case averaged over the blue dashed rectangle area in Fig. 8a are shown in Fig. 15. In comparison with CTRL, reducing urban areas decreases air temperature, while expanding urban areas increases air temperature. The air temperature change extends to about 1.8 km during the day and 0.2 km at night, with a nighttime maximum of 1.7°C near the ground. In general, urban land use (buildings) enhances vertical mixing, increasing daytime wind speed below 1 km, and decreasing wind speed above 1 km (Fig. 15c,d). In the nighttime, the urban buildings block the wind. However, in the later afternoon around 0900 UTC (1700 LST), the average wind speed in case U2C is larger than that in CTRL and smaller for FU. The wind field from these three cases and their differences are plotted at 0900 UTC in Fig. 16 to figure out the reasons for this. At this time, the wind is shifting from easterly upslope to westerly downslope, so the resulting stagnant wind during this transitional period is subject to effects of the land surface. In the CTRL case, UHI circulation (Figs. 16a,b,d) enhances the wind at the upwind side of Beijing city, but weakens the wind in other areas. In the FU case, the effect of UHI is more prominent (Figs. 16a,c,e). So UHI circulation reduces the wind speed averaged
over the blue dashed rectangle area in Fig. 8a. Therefore, the wind speed around 0900 UTC in the case U2C is maximum, and that in case FU is minimum among these three cases.

Because of urbanization, the specific humidity in the lower atmosphere decreases in the daytime because of less vegetation and hence less evaporation in the urban area (Fig. 15f). However, it increases at night likely because of enhanced wind speed (Fig. 17d), which may bring more humid air from rural areas to cities. In U2C, the specific humidity in the lower PBL increases in daytime and nighttime, as expected.

Figure 17 shows the difference in the 10-m wind field between the two sensitivity cases and the control case. At 0600 UTC (1400 LST) the PBL is convective with cells and rolls (Miao and Chen 2008), so the differences of horizontal winds are noisy. At 1800 UTC (0200 LST), the northerly downslope wind is stronger in U2C than in CTRL, while in FU it is weaker because of the effect of urban-induced circulation.

Miao and Chen (2008) showed that HCRs are the most common form of boundary layer convection in the urban area, because of its rougher surface, larger boundary layer wind shear, and a stability range appropriate to HCRS, while cellular convection tends to form over the rural area. The vertical velocity and horizontal wind vectors at 0600 UTC (1400 LST) 18 August 2005, about 384 m AGL, for cases with varying building height are shown in Fig. 18. Figure 19 shows a vertical velocity cross section oriented normal to the wind from four tests with varying building height and anthropogenic heat. Increasing urban building height decreases the wavelength (spacing) $\lambda$ of HCRs (Figs. 18, 19a,b), while increasing anthropogenic heat increases the height $H$ of HCRs (Figs. 19c,d). Hence the aspect ratio $\lambda/H$ of HCRs in urban areas (~1.5) is smaller than the typical value over natural landscapes (2–15) (Etling and Brown 1993; Atkinson and Zhang 1996).

5. Summary and conclusions

In this paper, the characteristics of UHI and PBL structures in the Beijing area are investigated using observations and the WRF/Noah/UCM coupled modeling system. The monthly mean UHI intensity for August 2005 reaches a maximum of 1.12°C at 1300 UTC (2100 LST). The intensity averaged for 14 no-rain days during August 2005 is much stronger, especially in nighttime with the maximum of 1.62°C. For 18 August 2005, the UHI largely follows the monthly mean pattern, reaching the maximum of 2.4°C in the evening, but with an urban cool island of ~0.35°C in the early morning. Synoptic weather patterns have more impact on UHI intensity in nighttime than in the daytime.

The coupled WRF model reasonably reproduces the majority of observed UHI for 18 August 2005. However, it does not capture the urban “cool” island in the early morning, and the daytime simulated UHI intensity is
somewhat too strong. The WRF simulated maximum UHI intensity of 2.9°C appears at 1400 UTC (2200 LST), being 0.5°C higher and 1 h earlier than the observation. While the WRF/Noah/UCM simulates air temperatures in urban areas fairly well, the daytime (nighttime) cold (warm) bias in rural air temperatures is a leading factor contributing to the disagreement between observed and simulated UHI intensity. Evaluation statistics indicate that urban canopy–level variables (e.g., temperature, wind speed) from WRF/Noah/UCM compare better with surface observations than traditional variables (e.g., 2-m temperature, 10-m wind speed).

Local circulations for 18 August 2005 in the Beijing area are dominated by mountain–valley winds, which are modified by UHI circulations. The WRF/Noah/UCM modeling system reproduces the timing of wind reversal reasonably well. At its early formation stage after sunset, the LLJ can be seen in the boundary layer over rural areas, but it is largely absent over urban areas because of wind attenuation. Only later does the LLJ appear over urban areas, but with weaker intensity and located higher in the boundary layer than that over rural areas.

Miao and Chen (2008) use WRF simulations and wind profiler observations to conclude that daytime convection in the urban area is mainly in the form of convective rolls, illustrating that the WRF/Noah/UCM modeling system can well capture boundary layer convective rolls and cells. Sensitivity tests for the present paper indicate that the increase of urban building height decreases the wavelength (spacing) of HCRs, while the increasing of anthropogenic heat increases the depth of HCRs. Hence the aspect ratio of HCRs in urban areas (~1.5) is smaller than the typical value over natural landscapes (2–15). Thus the presence of urban surfaces significantly impacts the formation of HCRs, while the details in urban structures seem to have less pronounced but not negligible effects on HCRs.

![Figure 19](image-url)
Sensitivity tests with WRF-Noah/UCM show that the expansion of urbanized areas increases absorbed solar radiation, sensible heat flux, ground heat flux, and the anthropogenic heat source, while decreasing latent heat flux. The air temperature increase in the urban area extends to about 1.8 km AGL during the day and to 0.2 km AGL at night, when the maximum of 1.72°C near the ground occurs. Urban land use (buildings) enhances vertical mixing during the day, increasing wind speed below 1 km and decreasing wind speed above 1 km, while it blocks and slows the wind at night. The humidity near the ground decreases in the daytime and increases in the nighttime because of urbanization.

Comparisons with observations demonstrate reasonably successful simulations of important urban surface and boundary layer structures, indicating the general adequacy of using the single-layer UCM in WRF. Nevertheless, our results may be limited by the single-layer UCM (its features are depicted in section 3) in which the urbanization only affects the surface layer directly. We plan to use a multilayer UCM (e.g., Dupont et al. 2004) that can explicitly influence the lower boundary layer through tall buildings to further investigate urban boundary layer structures in Beijing.

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REFERENCES


