Hindawi Publishing Corporation
Advances in Meteorology
Volume 2014, Article ID 602528, 11 pages
http://dx.doi.org/10.1155/2014/602528

Research Article

Impact of a Detailed Urban Parameterization on Modeling the Urban Heat Island in Beijing Using TEB-RAMS

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Received 12 December 2013; Revised 20 February 2014; Accepted 10 March 2014; Published 5 June 2014

Academic Editor: Klaus Dethloff

The Town Energy Budget (TEB) model coupled with the Regional Atmospheric Modeling System (RAMS) is applied to simulate the Urban Heat Island (UHI) phenomenon in the metropolitan area of Beijing. This new model with complex and detailed surface conditions, called TEB-RAMS, is from Colorado State University (CSU) and the ASTER division of Mission Research Corporation. The spatial-temporal distributions of daily mean 2 m air temperature are simulated by TEB-RAMS during the period from 0000 UTC 01 to 0000 UTC 02 July 2003 over the area of 116°E~116.8°E, 39.6°N~40.2°N in Beijing. The TEB-RAMS was run with four levels of two-way nested grids, and the finest grid is at 1 km grid increment. An Anthropogenic Heat (AH) source is introduced into TEB-RAMS. A comparison between the Land Ecosystem-Atmosphere Feedback model (LEAF) and the detailed TEB parameterization scheme is presented. The daily variations and spatial distribution of the 2 m air temperature agree well with the observations of the Beijing area. The daily mean 2 m air temperature simulated by TEB-RAMS with the AH source is 0.6 K higher than that without specifying TEB and AH over the metropolitan area of Beijing. The presence of urban underlying surfaces plays an important role in the UHI formation. The geometric morphology of an urban area characterized by road, roof, and wall also seems to have notable effects on the UHI intensity. Furthermore, the land-use dataset from USGS is replaced in the model by a new land-use map for the year 2010 which is produced by the Institute of Remote Sensing and Digital Earth (RADI), Chinese Academy of Sciences (CAS). The simulated regional mean 2 m air temperature is 0.68 K higher from 01 to 02 July 2003 with the new land cover map.

1. Introduction

Urban warming is much more rapid and evident than global warming [1–3]. The AH emission also plays an important role in determining the UHI intensity. The UHI phenomenon was observed in New York City [4]. Bornstein found that the average intensity of UHI was maximal near the surface but gradually decreased to zero at 300 m. Myrup [5] developed a general energy budget model to investigate the competing physical processes of reduced evaporation in the city center and the thermal heating of the city buildings and paving materials. Oke [6] measured air temperatures in and near the surroundings of Vancouver to provide the observational evidence for comparing an empirical model and a theoretical advective model simulated vegetation canopy and UHI. The theoretical model failed to reproduce the observations of UHI in Vancouver, while the empirical model performed quite well. Kim and Baik [7] verified a change in the average maximum UHI intensity over different seasons in Seoul, Korea. They found that the average maximum UHI intensity is weak in summer but strong in winter. Furthermore, the analyses showed that the maximum UHI is positively correlated with the previous-day maximum UHI, but negatively correlated with the wind speed, cloudiness, and relative humidity. Detailed reviews on the UHI effects and urban climate can be found in Arnfield [8] and Grimmond [9]. Arnfield assessed the advances of urban climate studies relating to atmospheric turbulence and exchange processes of energy and water at different scales. Grimmond summarized the importance of the observations in the urban area to understand urban climate and improve the model performance. Recently, researchers have observed more and more relationships between the climate change of cities and the UHI effects [10–12].

Beijing, an important international metropolis, has spread rapidly, markedly modifying the regional and local weather and climate characteristics. Ren et al. [13] studied the temporal change of the UHI intensity at a number of weather stations and found significant urbanization-induced warming on seasonal and annual time scales. Miao et al. [14] analyzed the UHI characteristics and boundary layer structures in Beijing using the weather research and forecasting (WRF) model coupled with a single-layer urban canopy model. The results show that WRF can reproduce the diurnal variation and spatial distribution of the UHI intensity and the diurnal cycle of wind speed and direction and the small-scale boundary layer convective cells. Furthermore, Zhang et al. [15] investigated the urban impacts on summer precipitation employing a mesoscale numerical model over a larger Beijing metropolitan area. They revealed that the rapid urban expansion is statistically correlated to summer rainfall reduction in the northeast areas of Beijing. Furthermore, there is no clear long-term trend in summer aerosol optical depth in Beijing. A mesoscale weather model with different land-use data is also used to analyze two selected heavy summer rainfall events in Beijing. Urban expansion produced less evaporation, higher surface temperatures, larger sensible heat fluxes, and a deeper boundary layer. In the current study, we apply the TEB-RAMS with a detailed urban parameterization scheme to study the UHI phenomenon over the metropolitan area of Beijing.

The versatile numerical prediction model RAMS has been successfully applied to the mesoscale simulation of meteorological characteristics [16–18]. Rozoff et al. [19] used a storm-resolving version of RAMS to simulate the urban atmosphere, and they found that the UHI characteristic plays an important role in initiating deep, moist convection downwind of the city over St. Louis, Missouri. The model can successfully simulate the atmospheric circulation of the planetary boundary layer from the hemisphere-scale down to the turbulence-scale, and it is more usually used in weather forecasting and regional-scale climate simulations [20–23]. Zhang et al. [24] used RAMS to study the UHI effect in the Chongqing area, and they found that the original RAMS model, without the single-layer urban canopy model, could not accurately simulate the UHI characteristics, whereas the accuracy was significantly improved when RAMS-Urban Canopy was used.

Recently, the consideration of the urban canopy and AH emission has drawn more attention to the UHI studies. However, the traditional mesoscale atmospheric models handle the urban canopy with the same parameterization scheme used for the vegetation canopy [25, 26]. Some land surface parameters, such as the soil constants, are changed in the conventional models to describe the urban features, which are far from being realistic. The urban canyon geometry and AH emission are not accounted for in such models. In the past decade, several urban canopy parameterization schemes were proposed and developed to investigate the surface energy balance and urban climate characteristics among others [27, 28]. In particular, Masson [29] presented the TEB model considering a canyon geometry structure that includes three types of surfaces: roof, wall, and road. The model was partially amended by Kusaka et al. [30] and Lemonsu et al. [31]. The amended model included the canyon orientation and the diurnal change of solar azimuth angle. Moreover, the land surface consisted of street canyons with different orientation. The TEB model has been successfully used to a large variety of applications, ranging from simulation of urban surface energy balance to air quality modeling [32–35]. Urban canopy models have now been coupled to different regional mesoscale atmospheric models, which are used to improve the representation of urban boundary layer meteorology [14, 36]. The TEB model accounting for the effect of the anthropogenic sensible and latent heat fluxes on all artificial surfaces seems to be able to contribute to the more accurate evaluation of the UHI phenomenon. In this work, the TEB-RAMS model is used to investigate and evaluate the UHI intensity in Beijing.

2. Study Areas, Data, and Methodology

We integrate the advanced version of TEB-RAMS over Beijing metropolitan area with four levels of two-way nested grids, as shown in Figure 1(a). The grid spacing and grid point numbers in latitude and longitude directions of these four domains are 36 km (80 × 80), 9 km (82 × 82), 3 km (80 × 80), and 1 km (83 × 83). The vertical grid contains 25 full sigma levels. Vertical grid stretch ratio is 1.1 and vertical grid spacing is 120 m up to 15 km height in the atmosphere. The simulation starts on 0000 UTC 01 July, 2003 and ends on 0000 UTC 15 July, 2003. The initial and lateral boundary conditions are provided by the ERA-40 reanalysis data product [37]. Figure 1(b) shows the spatial distributions of the vegetation types for grid 4, the finest grid, where the red raster represents the urban area of Beijing. The position of the intersection between the lines AB and CD is the location of Tian'An Men Tower, the center of Beijing.

The daily meteorological observation datasets were obtained from 1951 to present and were used for model evaluation. The ERA-40 reanalysis datasets with $1^\circ \times 1^\circ$ spatial resolution were used to provide TEB-RAMS including pressure-level air temperature, wind speed and direction, geopotential height, and relative humidity at 6-hour interval. The model uses sea surface temperatures (SST) of 1° global monthly climatological sea surface temperature data from the National Oceanic and Atmospheric Administration (NOAA). The land-cover maps from USGS during the period 1992-1993 [38, 39] and from RADI during the year 2010 are used to evaluate the urbanization effect on the UHI intensity in Beijing.

The overall goal of this study is to describe the general characteristics of UHI in the Beijing area. Due to limited computing resources, a one-day experiment, from 0000 UTC

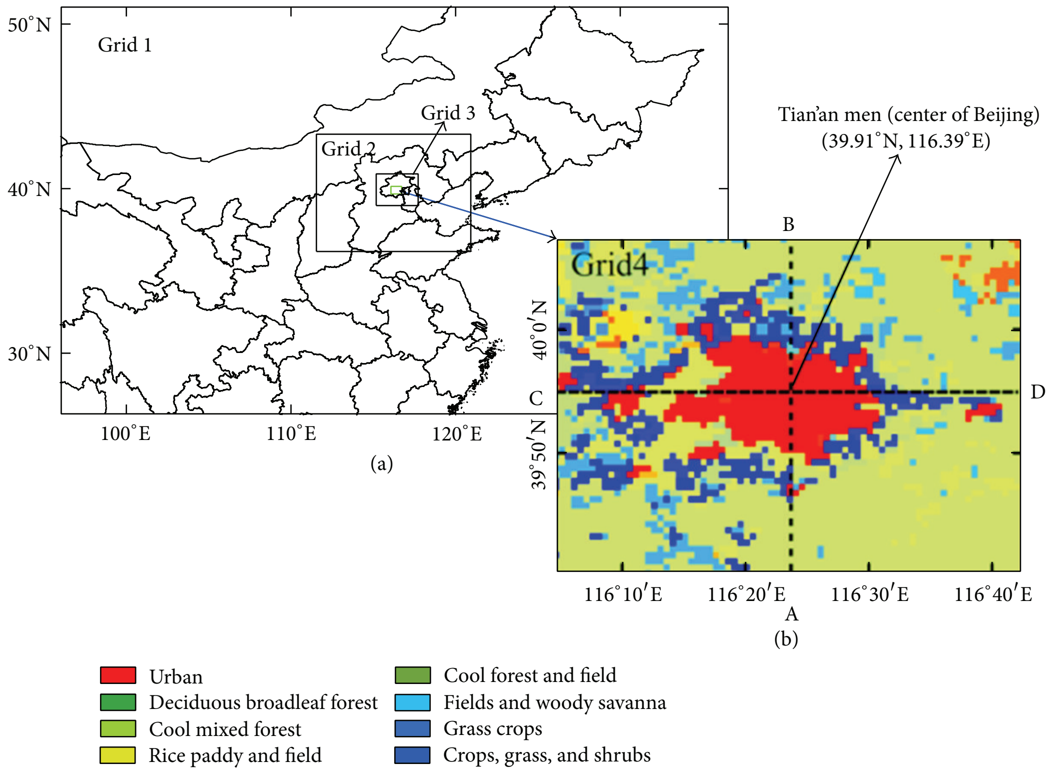


Figure 1: (a) Configuration of the four two-way nested domains used for the TEB-RAMS (LEAF3-RAMS) simulation in this study. The center of the fourth grid represents the metropolitan area of Beijing, and the central position is located in Tian'an Men Tower. (b) Beijing city with the innermost contour representing its most urban region. The red region represents urban category. The legend shows the vegetation types of the USGS land-use data.

Table 1: The main simulation parameters in the model.

RAMS6.1	Domain
Overlay areas	26.3~51°N, 96~136.6°E
Horizontal grids	80 × 80, 82 × 82, 80 × 80 and 83 × 83
Grid interval (km)	36, 9, 3 and 1 km
Vertical layers	25, 25, 25 and 25
Time integration (d)	From 00 UTC 01 to 00 UTC 15 July 2003
Time step (s)	30
LW radiation	Harrington
SW radiation	Harrington
Surface parameterization	LEAF3 and TEB
Forcing data (initial/boundary conditions)	ERA40 reanalysis data (6-h intervals, 1° × 1° resolution)

01 to 0000 UTC 02 July 2003, is performed and analyzed. This day is chosen because it is a clear day, and the UHI effect is easier to be discerned. The specific model parameters are listed in Table 1.

The Land Ecosystem-Atmosphere Feedback (LEAF) has evolved along with RAMS through the past two decades [26, 40, 41]. LEAF-3 represents fine-scale variations in surface characteristics using leaf area index, vegetation fractional coverage, albedo, and roughness length, among others. The traditional approach treating the urban canopy is similar to the vegetation canopy, in spite of the differences in the geometric features and thermal-dynamic characteristics between the urban surface and vegetated surface on relevant spatial scales. Therefore, a new urban parameterization scheme developed by Masson [29] was introduced and coupled to RAMS, called TEB-RAMS. The local urban geometry is defined in the TEB-RAMS model, while the usual bare soil formulation is used to represent cities in the old LEAF3-RAMS model. The dominant land-use categories in Beijing are urban land and crop/mixed farming. In the TEB-RAMS simulation, a detailed canyon geometric structure in the TEB scheme replaces the usual bare soil formulation or the simple one-layer plant canopy in the LEAF3 model. The TEB scheme, which is typically utilized to represent urban

Table 2: Input parameters for the TEB scheme in Beijing.

Parameters	Unit	Beijing
Geometric parameters		
Building fraction	—	0.5
Building height	m	60
Wall/plane area ratio	—	4.4
Canyon aspect ratio	—	3.0
Roughness length	m	3.0
Radiative parameters		
Roof, wall, and road albedo	—	0.15; 0.25; 0.1
Roof, wall, and road emissivity	—	0.9; 0.85; 0.94
Thermal parameters		
Roof, wall, and road thickness		0.05; 0.02; 0.05
Roof, wall, and road thermal conductivity		0.41; 0.81; 1.0103
Roof, wall, and road Thermal capacity		2110000; 1000000; 1240000
Temperature initialization		
Inside building temperature	°C	26.0
Anthropogenic heat sources		
Vehicular sensible heat source	W/m^2	200.0
Industrial sensible heat source	W/m^2	200.0

areas, can better represent the UHI effects than the LEAF3 scheme, as shown by Rozoff et al. [19]. In the present study, three numerical experiments are conducted to examine the individual model setup performance in terms of representing UHI effects. The first experiment is done by default LEAF3-RAMS model, the second experiment is done by TEB-RAMS without AH emission, and the third experiment is done by TEB-RAMS-AH, in which AH emission is introduced. Table 2 lists the input parameters of the TEB scheme for Beijing. Furthermore, the latest land-use map of 2010 developed by RADI is used to replace the earlier land-use map from USGS of 1992. The UHI effect is analyzed due to land use/land cover changes.

3. Model Evaluation and Comparison

Although RAMS has been widely used in climate modeling and weather forecasting in many countries, it has been used relatively less frequently in China. Therefore, it is especially important to evaluate its baseline performance against observations. The observations from the Chinese National Meteorological Information Center (NMIC) include 2,518 stations, which are part of the international data exchange.

Figure 2(a) shows the comparison of TEB-RAMS simulated the daily mean 2 m air temperatures and the observations from 01 to 15 July 2003 for the location of Guanxiangtai at 116.47°E, 39.8°N. The results show that the TEB-RAMS model successfully captures the daily variations of the observed 2 m air temperature during the simulation time period. The scattered plot of the observed and simulated daily mean 2 m air temperature records has a correlation coefficient of 0.81 (Figure 2(b)). Then the datasets from 18 automatic meteorological observation stations in the Beijing area were interpolated to TEB-RAMS grid 4 to evaluate the simulated spatial distribution of the 2 m air temperatures. The sites' coordinates are provided in Table 2. The spatial distribution of the UHI intensity for the observed data is exhibited in Figure 3. The results show that the spatial distribution of the observed temperatures is similar to the simulated results in Figure 5. Therefore, the TEB-RAMS model can reproduce the UHI intensity well.

Guanxiangtai station at 116.47°E, 39.8°N is in an urban area, while Miyun station at 116.87°E, 40.38°N is in a rural area. Figure 4 plots the daily mean 2 m air temperatures for both stations from 01 to 15 July 2003. The air temperatures at the Guanxiangtai station are found to be consistently higher than that of the Miyun station. The daily mean 2 m air temperature is 0.85 K higher in the urban area than that in the rural area. The maximum difference of the temperature is 2.5 K higher and the minimum difference of the temperature is −0.9 K lower, which are consistent with the classic UHI characteristics (Table 3).

Sensitivity experiments to compare the TEB-RAMS model with and without the AH emission, as well as with the default LEAF3-RAMS model, have been carried out to evaluate each of these models' simulated the UHI phenomenon for Grid 4, the finest grid, where the grid spacing is 1 km × 1 km. The main surface parameter for the TEB submodel is the building height, which was specified as 60 m for Beijing area. The spatial distributions of model simulated daily mean 2 m air temperatures for the period from 0000 UTC (1400 LST) 01 July 2003 to 0000 UTC 02 July 2003 for the different models are displayed in Figure 5. The areas 116.3°E~116.5°E and 39.85°N~39.97°N represent urban underlying surface. The ranges 116.5°E~116.7°E and 39.85°N~39.97°N represent suburb underlying surface. The regional mean difference of the 2 m temperature in the above area is defined as the UHI intensity. Heat is released into the atmosphere due to

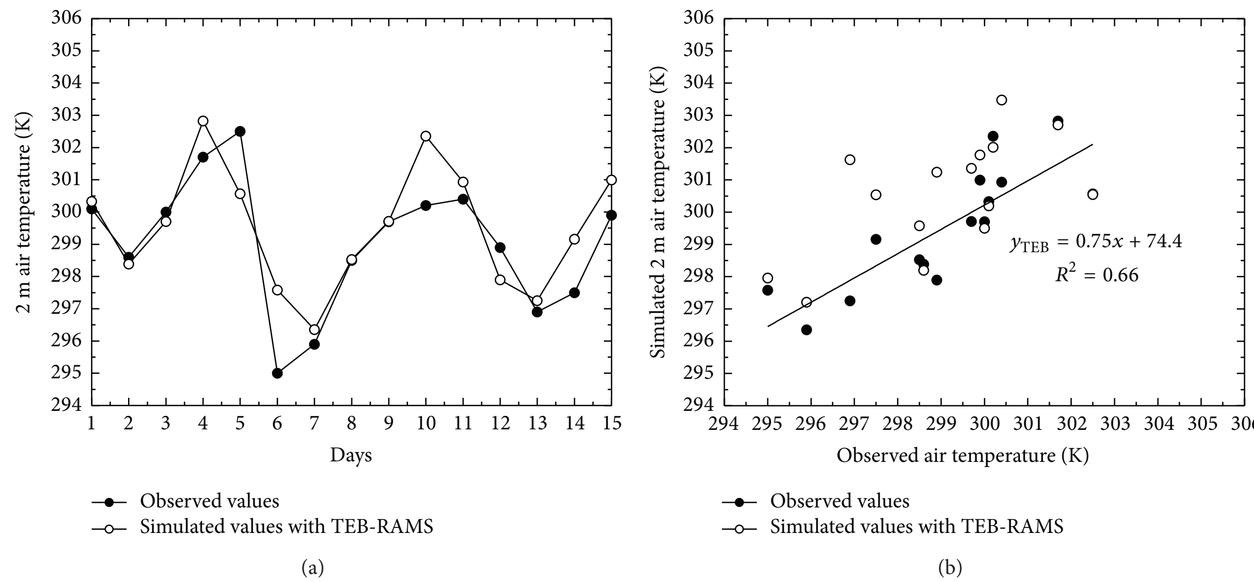


Figure 2: (a) Comparison of the TEB-RAMS model simulated daily 2 m air temperatures with observations from 01 to 15 July 2003, at the Guanxiangtai station. The black filled circle line represents the observed 2 m air temperature in Beijing, and the black open circle line represents the TEB-RAMS simulated 2 m air temperature. (b) The scatter diagram of correlation relationship between the simulated 2 m air temperature and the observed temperature. The black line represents the linear fit trend.

Table 3: Coordinates of the daily temperature measurement sites.

Stn_num	Stn_name	Lon	Lat	Mean T (°C)
54399	Haidian	116.28	39.98	27.8
54433	Chaoyang	116.48	39.95	26.4
54511	Guanxiangtai	116.47	39.8	27.1
54514	Fengtai	116.25	39.87	26.7
54398	Shunyi	116.63	40.12	26.8
54412	Tanghekou	116.63	40.73	23.9
54416	Miyun	116.87	40.38	26.3
54419	Huairou	116.63	40.32	27
54421	Shangdianzi	117.12	40.65	24.7
54424	Pinggu	117.1	40.15	26.5
54594	Daxing	116.33	39.75	26.4
54501	Zhaitang	115.68	39.97	24.5
54505	Mentougou	116.12	39.92	26.3
54596	Fangshan	116	39.7	26.1
54597	Xiayunling	115.73	39.73	24
54406	Yanqing	115.97	40.45	24.2
54410	Foyeding	116.13	40.6	20.8
54513	Shijingshan	116.18	39.93	26.9

the effect of human activity, especially domestic heating and combustion from industry. Domestic heating as a default value is 26°C (Table 2). The two main combustion sources in the TEB model are traffic and industry. The heat fluxes released into the atmosphere directly are averaged on the town surface. Table 2 lists vehicular and industrial sensible heat source. The AH values are higher than those shown in the literatures [14, 24] considering the rapid urbanization of Beijing. The spatial distribution of 2 m air temperatures using TEB-RAMS-AH is shown in Figure 5(a). There is an evident warming effect for the air temperatures at 2 m, particularly in central Beijing. It is found that the air temperature at 2 m over the metropolitan area of Beijing is approximately 2 K higher than that over the suburbs of Beijing. Figures 5(b) and 5(c) also show the similar UHI phenomenon in Beijing, in which the temperatures of city area are 1 K warmer than the surrounding areas for both figures. In addition, the spatial distributions of the UHI characteristics are consistent

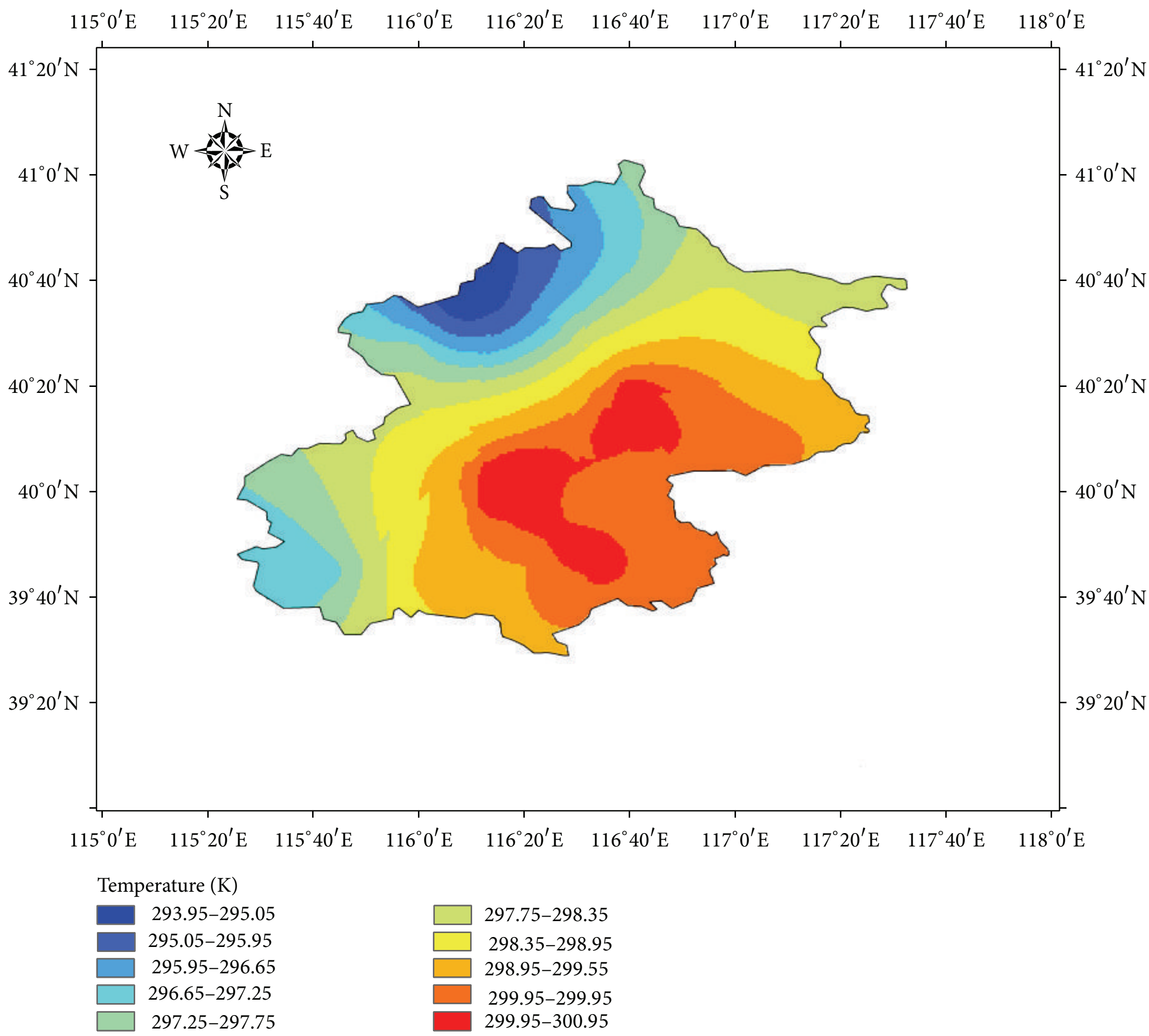


Figure 3: Spatial distribution of the observed daily mean temperature (K) from 01 to 02 July, 2003.

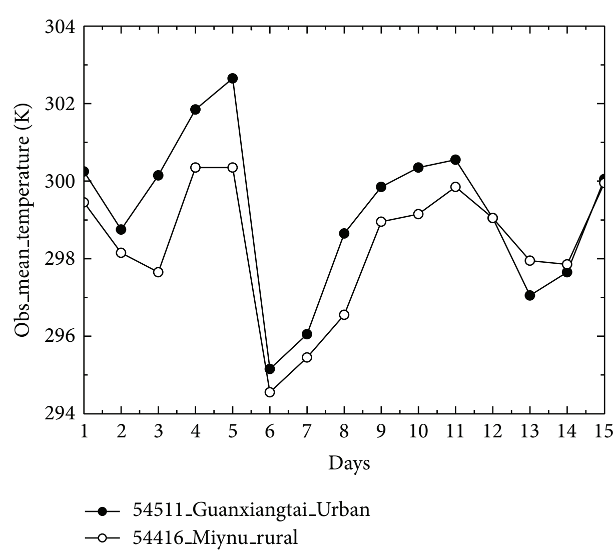


Figure 4: Comparison of the observed daily mean air temperature between the Guanxiangtai and Miyun stations from 01 to 15 July, 2003. The black filled circle line represents the observed temperature at the Guanxiangtai station, and the black open circle line represents the temperatures at the Miyun station.

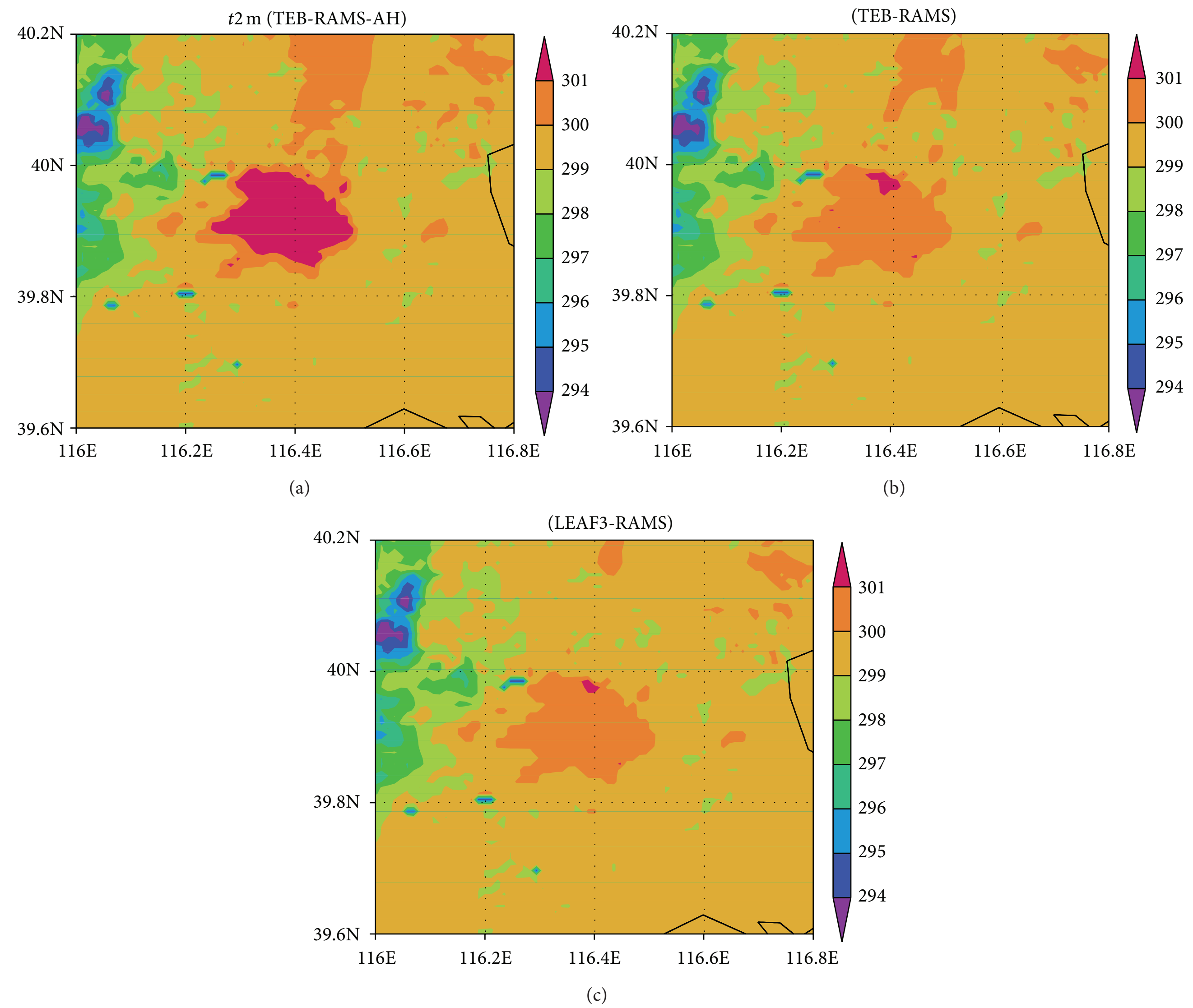


FIGURE 5: (a) Spatial distributions of model simulated daily mean 2 m air temperature (K) from 0000 UTC (1400 LST) 01 to 0000 UTC 02 July 2003 using the TEB-RAMS-AH model. (b) Same as in (a) without AH emission. (c) Same as in (a) but employing the LEAF3-RAMS model.

with the spatial distribution of the urban area map shown in Figure 1(b). The modeled heating intensity of the UHI phenomenon decreases in the following order: TEB-RAMS-AH, TEB-RAMS, and LEAF3-RAMS.

The spatial distributions of the differences of the simulated daily mean 2 m air temperatures for the different schemes are displayed in Figure 6. The simulated temperature from TEB-RAMS-AH is 0.6 K higher than that without AH and the absence of TEB (LEAF3-RAMS) in Figure 6(c). The maximum difference in 2 m temperature between the TEB-RAMS-AH and LEAF3-RAMS schemes is approximately 1 K. In addition, the temperature from TEB-RAMS is slightly higher than that of LEAF3-RAMS, as shown in Figure 6(b). A detailed urban canopy parameterization scheme, called TEB, uses a generalization of local canyon geometry with three surface types: roof, wall, and road. The TEB model produces a higher UHI intensity when compared with a simple urban parameterization based on the LEAF3 model for central Beijing for the simulation time period.

Variations in the simulated daily averaged 2 m air temperature along the meridional and zonal distributions are examined by two cross sections in Figure 7. Figure 7(a) shows the 2 m air temperature variations at the 39.91°N position along the meridional distribution. The 2 m air temperature is higher near the points at 116.18°E, 39.91°N and 116.25°E, 39.91°N than other places in the vicinity. Furthermore, Figure 7(b) shows the 2 m air temperature variations at the 39.91°N position along the zonal distribution. The 2 m air temperatures are also higher in urban underlying surface than that in the vicinity, as shown in Figure 1(b). We also found that the daily mean 2 m air temperatures are clearly higher in the central area of Beijing than in other adjacent locations. Moreover, the order of the 2 m air temperature

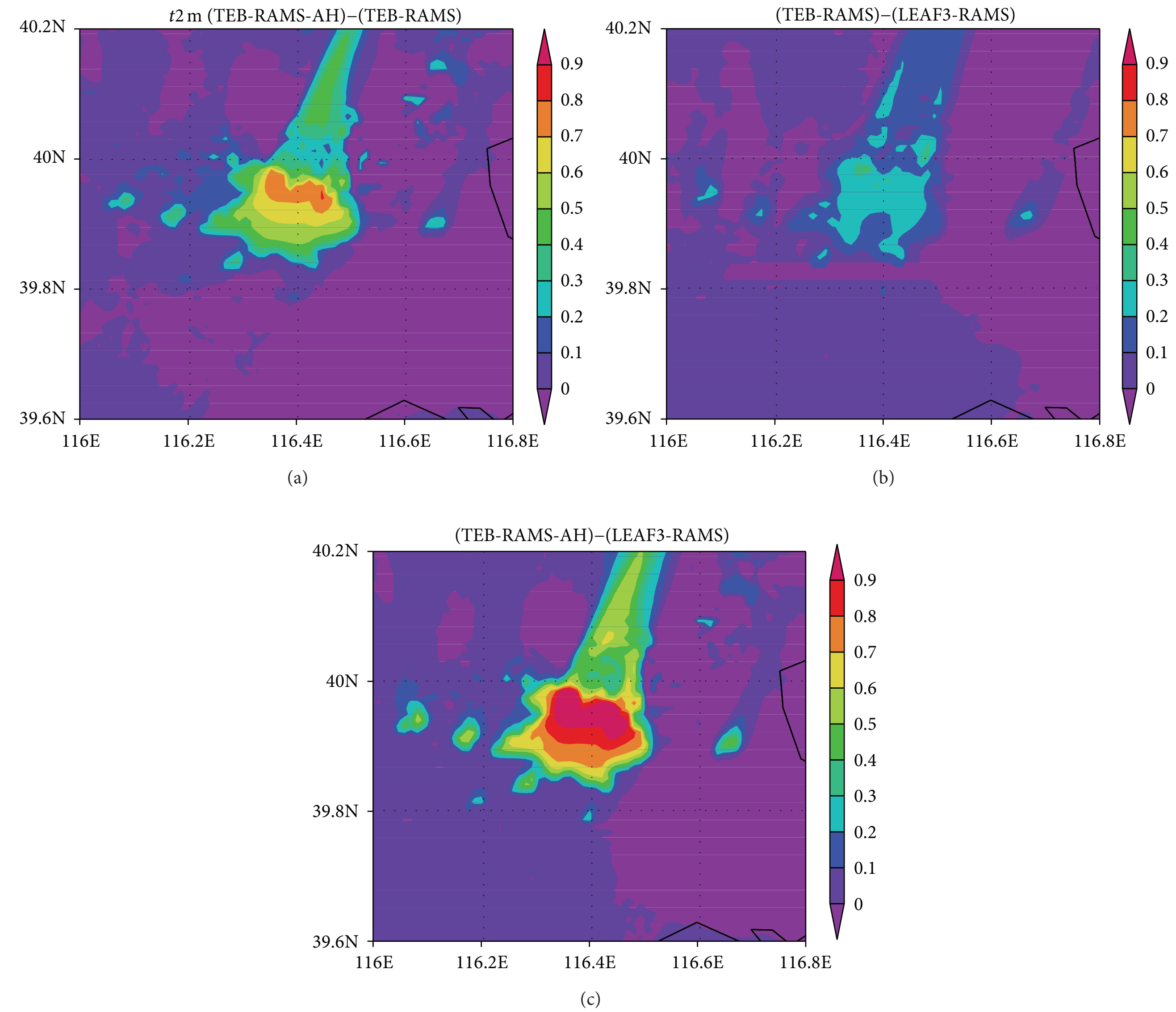


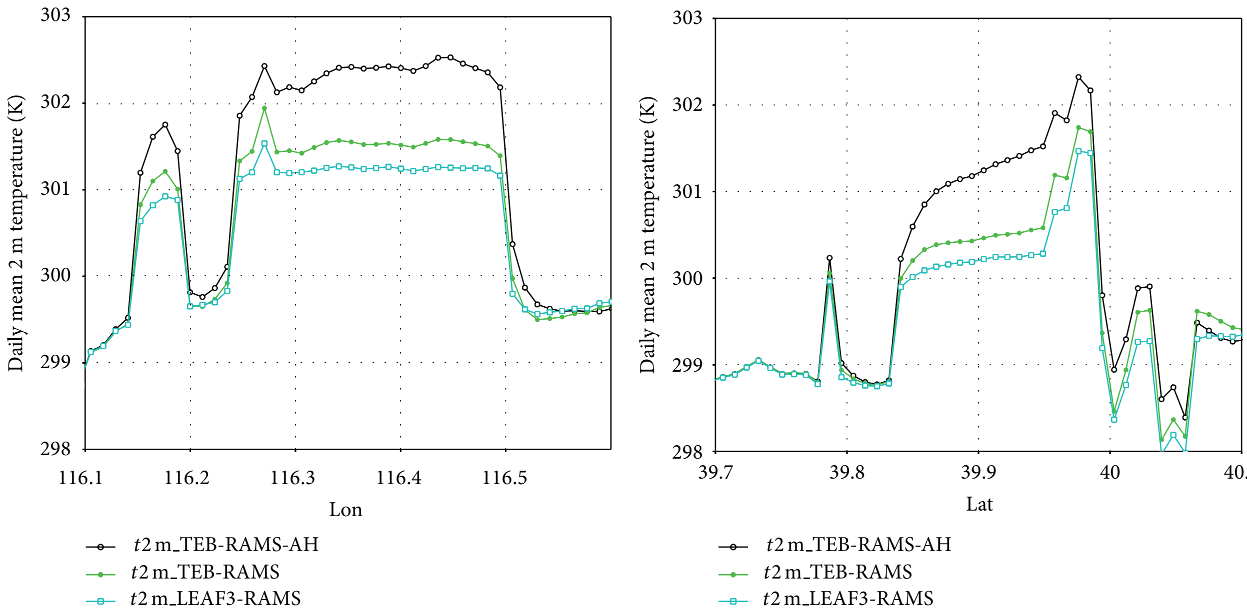
FIGURE 6: (a) Spatial distribution of the difference of model simulated daily mean 2 m air temperature (K) for the period from 0000 UTC (1400 LST) 01 to 0000 UTC 02 July 2003 between the TEB-RAMS-AH and TEB-RAMS models. (b) Same as in (a) but for the TEB-RAMS and LEAF3-RAMS models. (c) Same as in (a) but for the TEB-RAMS-AH and LEAF3-RAMS models.

variations from high to low is TEB-RAMS-AH, TEB-RAMS, and LEAF3-RAMS. The land cover dataset of USGS 1992 is used in the model [38, 39], while Beijing has gone through major development spurt during this period. Therefore, a new land-use dataset of 2010 from RADI was obtained in order to more realistically evaluate urbanization effect. Shown in Figure 8 is the latest total area of the urban surface in Beijing, approximately 1000 km^2, which is more than twice as that is defined by the USGS land-cover dataset (Figure 1(b)), which is about 400 km^2.

Two numerical experiments were conducted using TEB-RAMS, with one experiment based on the new land cover dataset of 2010, and the other using land cover map of USGS 1992. In Figure 9, the difference of the regional mean 2 m air temperature between the two different land cover maps is plotted, and the domain-averaged temperature is 0.68 K warmer with the new land cover map. This demonstrates that the urban underlying surface plays an important role in determining the UHI effect. The rapid urbanization in Beijing has gradually changed the characteristics of the underlying surface and atmospheric environment.

4. Conclusions and Discussion

In this paper, the TEB-RAMS model is used to investigate the UHI intensity over the metropolitan area of Beijing with four levels of nested grids. It is found that the TEB-RAMS model has the ability to represent the particular features of urban regions used in operational numerical models. The correlation coefficient is approximately 0.81 for the observed



(a) (b)

Figure 7: (a) Cross section of the daily mean air temperature at 2 m along line CD as shown in Figure 1(b) indicated by the black open circle line (TEB-RAMS-AH), green filled circle line (TEB-RAMS), and blue open square line (LEAF3-RAMS). (b) Same as in (a) but along the line AB also shown in Figure 1(b).

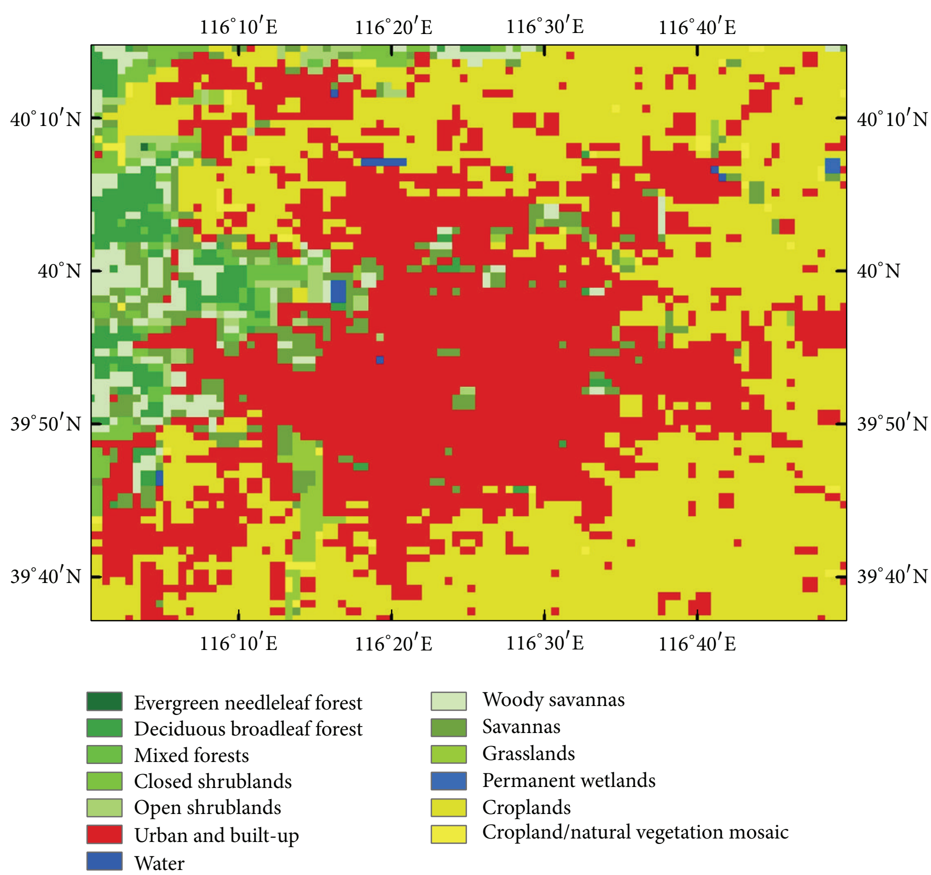


Figure 8: Spatial distribution of 2010 land use.

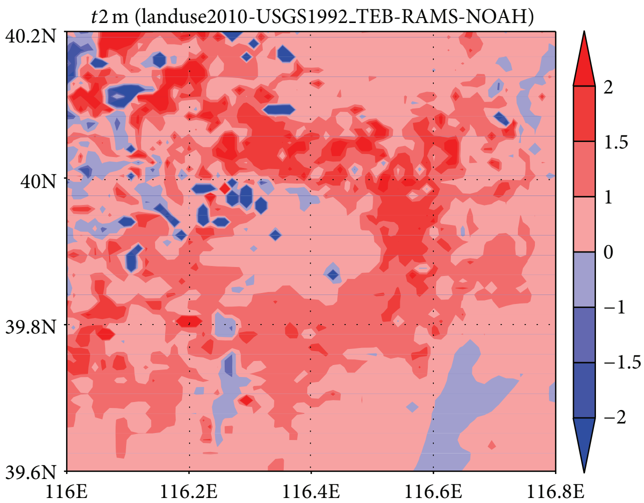


Figure 9: Spatial distribution of the 2 m air temperature difference (K) (landuse2010-USGS1992).

and modeled daily mean 2 m air temperatures. The spatial distribution pattern of the model simulated 2 m air temperature with TEB-RAMS is also consistent with observations. The time series of 2 m air temperature simulation using TEB-RAMS agrees well with that of station observation.

The difference of the air temperature between the Guanxiangtai station and the Miyun station represents the UHI intensity during the time from 1st to 15th July 2003. It is found that daily averaged 2 m air temperature in the urban area is 0.85 K higher than that of the rural area. Sensitivity experiments using TEB-RAMS are conducted to demonstrate the differences in 2 m air temperature between the urban and rural areas. The results show that the 2 m air temperature simulated both by TEB-RAMS and LEAF3-RAMS of the urban area is 1 K warmer than that of the rural area. Moreover, the daily mean 2 m air temperatures are consistently higher in the urban area than that in the area of other vegetation types as are shown along the meridional and zonal cross section. The spatial distribution of UHI closely follows the spatial distribution of urban land-use area, as exhibited in Figure 1(b). Furthermore, sensitivity studies of TEB-RAMS with and without AH source and LEAF3 scheme are compared for the Beijing area. The results show that the geometric morphology of an urban area characterized by road, roof, and wall seems to have notable effects on the UHI intensity, implying the need for TEB scheme. It is also found that the 2 m air temperature in urban area is approximately 2 K higher than in suburb when AH is considered and TEB scheme is included in RAMS. The TEB-RAMS-AH simulated temperature at 2 m is 0.6 K higher than that of LEAF3-RAMS over the metropolitan area of Beijing in the fourth nested grid. The order of the simulated 2 m air temperature from high to low is TEB-RAMS-AH, TEB-RAMS, and LEAF3-RAMS, respectively. Moreover, the UHI intensity is the largest for TEB-RAMS-AH model compared to the other two models. Finally, the land-use dataset of 1992 from USGS is replaced in the model with a new land-use dataset of 2010 from RADI. The results highlight that the urbanization enhances the UHI intensity. The difference of the regional mean 2 m air temperature is 0.68 K warmer from 01 to 02 July 2003 due to the effect of rapid urban expansion.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The authors would like to acknowledge the support from the National Basic Research Program of China (973 Program, Grant no. 2010CB428502), the National Natural Science Foundation of China (Grant nos. 40930530 and 41075112), and the Program of the Chinese Academy of Sciences (Y1S02600CX). Dr. Lu would like to acknowledge the support of NSF AGS-1219645.

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