Simulation of the urban heat island under the background of urbanization around Guangzhou

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Abstract

This paper simulated a heat wave event which occurred around Guangzhou during early August, 2012 by a weather research and forecasting (WRF) model coupled with an urban canopy model (UCM) at a horizontal resolution of 1 km. Three numerical simulations with new land-use data representing different urbanization scenarios and an default simulation with Modis land-use data were performed. The land-use data of 2012 was extracted from the Remote sensing(RS) data of year 2012 produced by the Landsat-7 satellite,then based on satellite-measured night-time light data and the normalized difference vegetation index(NDVI), a human settlement index was used to represent the current urban land-cover and define three urban land subcategories in the UCM. Using up-to-date urban land use data,which obtained as described above, simulation results agreed well with observation. The coupled WRF/UCM model reasonably reproduced the best 2-m temperature evolution and the smallest minimum mean-root-square-error as compared other experiments. The experiments coupled WRF/UCM could capturing the temporal characteristics of UHI intensity more accurately. The UHI intensity is gradually increasing after midday and becomes strongest at night, while it graduallydecreases in the morning and even gets negative at noon. The result showed that UHI intensity peak reached a maximum value of 3.0 °C at 1900 LST around sunset. Research indicates that the land-use change have a great impact on the simulation result. Comparisons among the results of four sensitivity runs showed that classification of three urban land subcategories in the experiments coupled UCM contributed 0.58℃ to lift the maximum UHI intensities,and the maximum up to 1.58℃ to UHI intensities. Anthropogenic heat release respectively contributed maximum 0.89 °C to the simulated UHI effects.

Keywords

WRF/UCM modeling system; Numerical simulation; Urban heat island; Anthropogenic heat

1. Introduction

Urbanization is a population shift from rural to urban areas, and the ways in which society adapts to the change. It predominantly results in the physical growth of urban areas. Urbanization level on behalf of a country and regional economic, cultural, social, scientific and technological level. On the other hand, concentrating on economic growth and social roles in the urban areas resulted by rapid progress in industrialization and urbanization, unplanned and hasty urbanization in modern cities, has also caused environmental problems including an increase in energy consumption, a change of the local climate such as the climate change and higher amounts of air pollution, especially during the last three decades. One of the results is a consistent rise in temperature in the urban atmosphere [1]because of the land-use changes and accompanying effects on physical processes governing energy, momentum and matter exchange between land surface and the atmosphere[2,3,4,5].

In recent years, studies of the Urban Heat Island (UHI) have high lighted the climatological aspects belonging to it

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[6]. The UHI is most pronouncedunder calm and clear nights [7]and the main contributing factors include: (1) changes in the physical characteristics of the land surface, replacement of natural vegetation by impervious surfaces resulting in alterations in the surface energy balance; (2) changes in the near-surface flow attributed to the complicated geometry of streets and tall buildings. and (3) higher anthropogenic heat release.

The weather research and forecasting (WRF) model coupled with the urban canopy model (UCM) was developed as a community tool for studying urban environmental issues by Chen [8]. S. Grossman-Clarke *et al.*[9]demonstrated that urban development and accompanying land-use changes can make significant contribution to extreme heat events by performing simulations using land-use data in different years with the Noah Urban Canopy Model in WRF. Hjelmfelt et al. [10] showed that with the increasing of ground surface roughness, the boundary layer convection enhanced.Zhang et al.[11] simulated the urban heat island and compared with observation in Baltimore ,USA, which shown that WRF model generally performs efficiently on ground surface temperature. The result certainly the role of WRF in evolution the effect of land use analysis on urban heat island.

With the urban building density increases, the three-dimensional structure of buildings changed transmission of solar radiation, atmospheric and terrestrial longwave radiation. Coupling an urban canopy model (UCM) in mesoscale models for describing in greater detail the thermodynamics and dynamics of cities has been very important in the development of model forecasting techniques.The WRFcoupled UCM model has been applied to many regions by many researchers such as Miao[12](Beijing,China) , Meng[13](Guangzhou,China), Chen[14](Houston,USA), Kusaka[15](Tokyo,Japan).All the research find that UCM models have improved the description of urban thermodynamic and dynamic effects and the simulation of thermal storage effect,flow field and precipitation distribution, as they incorporate the buildings' role in blocking radiationand reflecting shortwave and longwave radiation[16][17][18].

Higher anthropogenic heat release make the urban area heat higher than suburb area, which lead to higher urabn heat island intensity.Mai[19] evaluate the impacts of the changeod land cover and anthropogenic heat on the urban heat island in Pearl Rvier Delta region(China) by using WRF couple with UCM. Chen [20]comparisons among the results of four sensitivity runs in WRF couple UCM model system showed that urban land use, classification of three urban land subcategories,and consideration of anthropogenic heat release respectively contributed 56.8% (0.42 °C),13.5% (0.10 °C), and 29.7% (0.22 °C) to the simulated UHI effects in Hangzhou,China.

In this paper, the mesoscale WRF model and the UCM model are used to simulate the formation of a high-temperature weather in the area of Guangzhou and investigate the performance of WRF/UCM models with different geographical model. The more important is to evaluate the relative contributions of updated urban land use data,UCM and anthropogenic heat to the simulated UHI effects.

2. Data sources and methodology

2.1 Study area

This study is operated in Guangzhou which is located in south China. It is the capital and largest city of Guangdong province and the 3rd largest Chinese city as the city owned a population of 12.78 million of the 2010 census [21]. Located in the south-central portion of Guangdong, Guangzhou spans from 112° 57' to 114° 03' E longitude and 22° 26' to 23° 56' N latitude. Located just south of the Tropic of Cancer, Guangzhou has a humid subtropical climate which is influenced by the East Asian monsoon. Summers are wet with high temperatures, high humidity and a high heat index. The hottest period in summer usually lasts from Jul. 11th to Aug. 20th, whose average period is 41 days[22]. The mean annual temperature of the city is 22.3 °C, with monthly daily averages ranging from 12.3 °C inJanuary to 28.4 °C in July.

Guangzhou is also expanding at a very high speed. From the statistical data on China City Statistical Yearbook, we can realize that the constructed area in Guangzhou city has increased more than 4 times since the year 2000, which is much faster than the average expansion pace in the whole China. Such tremendous urban expansion, with increasing built-up areas and human activities, causes remarkable modifications to the underlying surface properties, thereby significantly enhancing the UHI effects. Previous studies show that the UHI is a significant contributor to the regional warming in this area[13]. In this study, the study area covers the 7 main districts in Guangzhou city where undergoing a fast urban expansion.

2.2 Model configuration

The WRF version 3.2 model coupled with a sophisticated single-layer UCM was used in this study. Three one-way nested domains with 72 × 72, 101 × 101, and 121 × 121 grid points and grid spacings of 25, 5and 1 km, respectively, were used (Fig. 1). The coordinates of the domain center is 22.116˚ and 113.5189˚. Nesting of the 3 calucation domains and their descriptions are shown in Fig.1. The largest domain of domain 1 covers the main part ofthe southern China and the second domains covers the whole Guangdong area. Main districts of Guangzhou were covered in Domain 3.

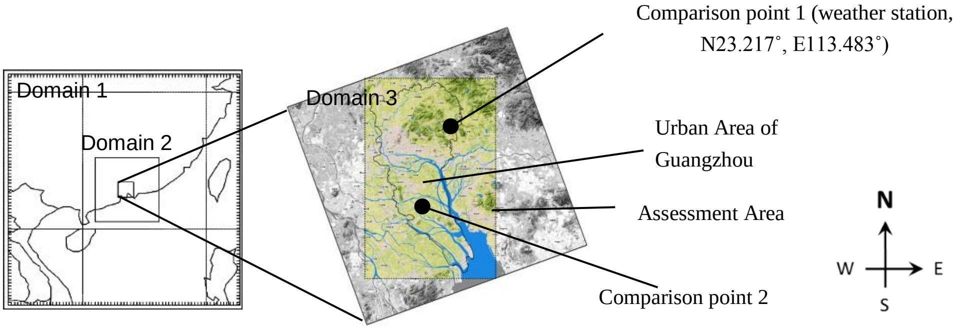


Fig.1 Configuration of the calculation domains and assessment area which contains 7 main districts of Guangzhou

The parameterization schemes used in our simulation are listed in Table 1, including long /short wave radiation processes, planetary boundary layer processes, land surface processes and microphysical processes, etc. In the WRF model, a single-layer urban canopy model was implemented in the NOAH land surface model to represent the thermal and dynamic effects of urban buildings, including the trapping of radiation within the urban canopy. The UCM standard values for heat capacity, conductivity, albedo, emissivity roughness length for heat and momentum of roof, road, and wall surface were employed [15]. The building height of three categories were set CIT 30m,HIR 21m andLIR 9m,the road width sespectively set for 20m,12m,7.8m. Initial and lateral boundary conditionswere taken from the National Centers for EnvironmentalPrediction (NCEP) Global Forecast System Final Analyses(horizontal resolution of 1° × 1°) with 6-h intervals.

Table 1. WRF configurations

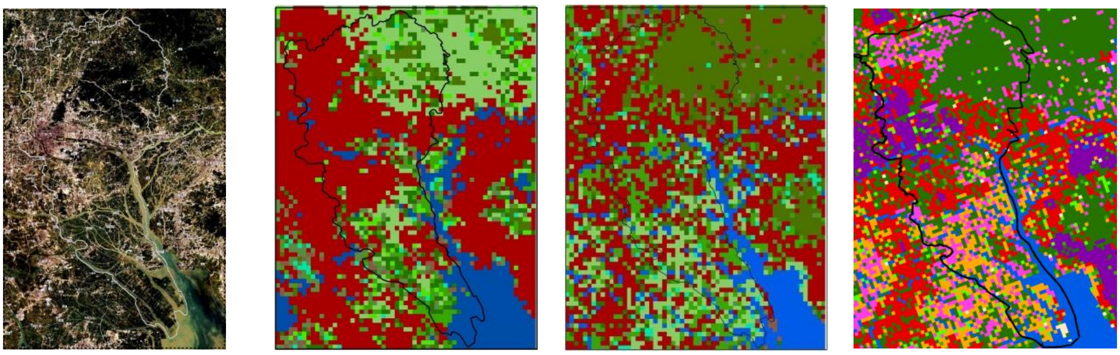
Time	2012-08-01-08:00 ---- 2012-08-03-08:00(GMT)
Meteorological data	National Centers for Environmental Prediction Final Operational Global Analysis data
Long wave radiation	RRTM longwave radiation scheme
Surface layer	Monin-Obukhovscheme
Land surface	Noah land-surface model + Single-layer urban canopy model (UCM)
Cumulus	Kain-Fritsch (new Eta) scheme
Short wave radiation	Dudhia scheme
Micro-physics	WRF Double-Moment 6-class
Boundary layer	Yonsei University (YSU) PBL

2.3 Update of land use data

Default land-use data (USGS 24-category) used in the WRF model are based on 1-km Advanced Very High

Resolution Radiometer data obtained from 1992 to 1993,which is considered outdated .because it fails to represent the rapid urban expansion in the past decade in China.WRF model released after version 3.1 provides an alternative land-use dataset which is based on the Moderate Resolution Imaging Spectroradiometer 2001 (MODIS) satellite products[23], but city area in this geographic model seems to be too large (Fig.2(2).

In this study, the land-use data of LU2012 (Fig. 2(3)) was extracted from the RS data of year 2012 produced by the Landsat-7 satellite. For Landsat 7 RS dataset, its resolution is 30 m and this dataset includes 9 bands of RS data with different wavelength ranges. Land-use information can be extracted from a combination of several of the 9 bands of RS data using the supervised classification method in IDRISI Selva, which is developed by the Clarklabs[24]. This extracted LU2012 data was then imported into GIS (geographic information system) for classification. Here, the MODIS 20-category was used for classification instead of the 24-category in USGS as geographic model in Domains 1 and 2 were both set to be MODIS in simulation.



(1) Satellite image 2012 (2) MODIS (3) Lu2012 (4) Lu2012-AB

Evergreen Needleleaf Forest; Evergreen Broadleaf Forest; Mixed Forests
Shrubland; Permanent wetlands; Croplands
Urban and Built-Up; Barren/Sparsely Vegetated; Water
Commercial; Hi-den Res; Low-den Res

Fig.2 Comparison geographic models with the satellite color image.

In addition, both USGS 24-category and MODIS 20-category land use data consider only one urban land category and thus cannot reproduce urban effects on local climate caused by the inhomogeneity in an urban area.

In the present study, HSI was used for deriving up-to-date urban land use data and specifying detailed urban land use categories in the UCM (i.e., CIT, HIR, and LIR). HSI data were obtained from a combination of nighttime light imagery and the normalized difference vegetation index (NDVI) [25], as expressed by Eq. (1).

$$HSI = \frac{(1-NDVImax)+\mathrm{OLSnor}}{(1-\mathrm{OLSnor})+\mathrm{NDVImax}+\mathrm{OLSnor}\times\mathrm{NDVImax}} \qquad (1)$$

where OLSnor is the normalized value [OLSnor= (OLS-23)/(OLSmax-23)] of the 2012 Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) image[26] (Elvidge et al., 1997, 1999, 2001). A threshold of 23 was selected to minimize the effects of blooming, a phenom- enon observed in DMSP/OLS nighttime imagery. OLSmax is the maximum value in the 2012 DMSP/OLS nighttime ligh image.

To separate human settlements from bare land effectively and remove the effect of cloud contamination, 2012 multi-temporal SPOT NDVI images[27]at a resolution of 1 km × 1 km were used to generate a new NDVI composite index, as shown in Eq. (2).

$$NDVImax = MAX(\mathrm{NDVI1}, \mathrm{NDVI2}, \dots, \mathrm{NDVI23}) \qquad (2)$$

HSI values were used to classify urban land in Guangzhou into the following subcategories: (1) pixels with HSI values≥ 80^{th} percentile represented CIT areas; (2) pixels with HSI values between the 30th and the 80th percentile represented HIRareas; and (3) pixels with HSI values ≤ 30th represented LIR areas. MODIS 20-category land use data were updated with the new urban land cover data to represent up-to-date urbanization conditions in Guangzhou. The non-urban land use categories were not modified[20]. We got the land use data and shown in Fig.2(4).

2.4 Number experiments

To investigate the relative effects of land use, UCM and anthropogenic heat release on the urban thermal environment, we designed four sensitivity runs with different urban-ization scenarios(Table 2). The conducted sensitivity experiments were as follows: (1) an experiment run used MODIS land use data default in WRF; (2) an experiment based on updated urban land cover data in 2012 without three additional subcategories and without corresponding anthropogenic heat release (here after referred to as the Lu2012 run); (3) an experiment based on the updated urbanland cover data in 2012 with three subcategories and coressponding anthropogenic heat release (here after referred to as the Lu2012-A run); and (4) an experiment on the updated urban land cover datain 2012 with three subcategories, but without anthropogenic heat release (hereafter referred to as the Lu2012-B run). The physics schemes were kept the same for all the runs.

Table 2 Experiments design

Experiments	Urban canopy	Land use categories	Anthropogenic heat release
Modis	No	20(Modis)	No
Lu2012	No	20(Modis)	No
Lu2012-A	yes	33(Modis+CIT+HIR+LIR)	Yes (90 50 20)
Lu2012-B	yes	33(Modis+CIT+HIR+LIR)	No

3.Results

3.1 Model validation

To validate the performance of the developed modeling system,we compared all the simulation results with weather stastion observations. Two points were selected, the comparison point 1(weather station)(Fig.1) is located in the suburban area and the land-use changes little in this place. The comparison point 2 is located in the urban area and is experiencing urbanization.

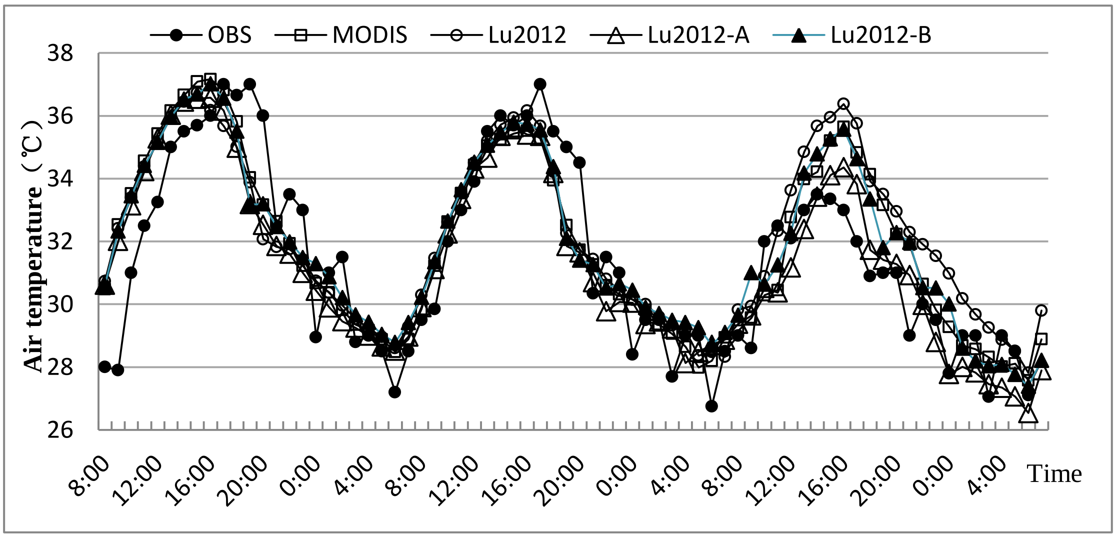


Fig.3 Comparison of simulated air temperature at 2m height in four experiments with observations at point 1

All of the experimental schemes have better reproduction of the diurnal variation of temperature, though with varying magnitudes. Fig.3 compares the observed and modeled 2m height temperature at suburban point. A statistical analysis of the simulations root-mean-aquare-error reveals that the Modis has an value of **2.41**, Lu2012 case **2.00**,Lu2012-A case**1.46**, and Lu2012-B **1.58**, respectively. Temporally, the Lu2012-A experiment is the best in reproducing the

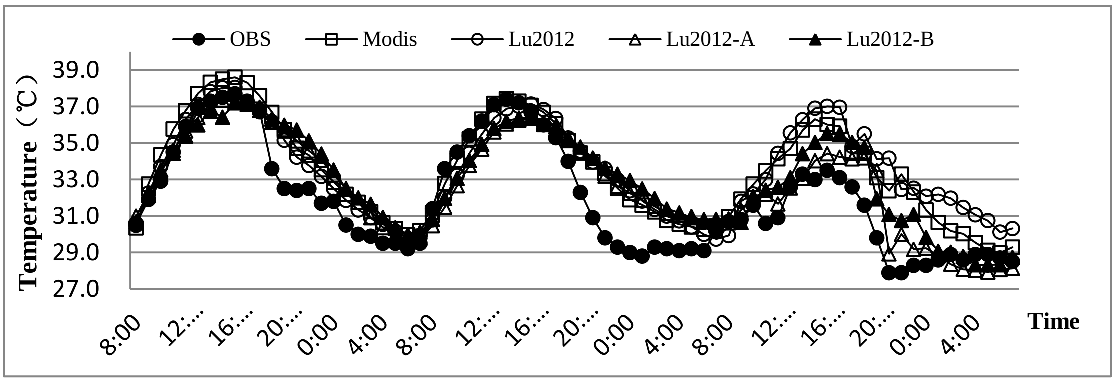


Fig.4 Comparison of simulated air temperature at 2m height in four experiments with observations at point 2

variation of suburban temperature, which can be also find urban point in Fig.4. The Lu2012-A experiment enjoys the lowest temperature at nighttime than anyother experiments. On 1st and 2nd August, the maxmum temperature time of simulation is earier than observation.The simualtion results is smaller than observation in daytime,but larger in nighttime.On 3rd August, there are the same variation tendency between simulation and observation,and all day the simulation larger than observation, but Lu2012-A has a good performance. Compared with the last two experiments, the Modis and Lu2012 experiments produces simulations that deviate the most from the observations, as evidently shown higher temperatures for all day. It is caused by the lack of UCM model ,which can realistic description buildings' role in blocking radiationand reflecting shortwave and longwave radiation and then improved the description of urban thermodynamic and dynamic effects in the simulated domain.

Fig.4 compares the observed and modeled 2m height temperature at urban point

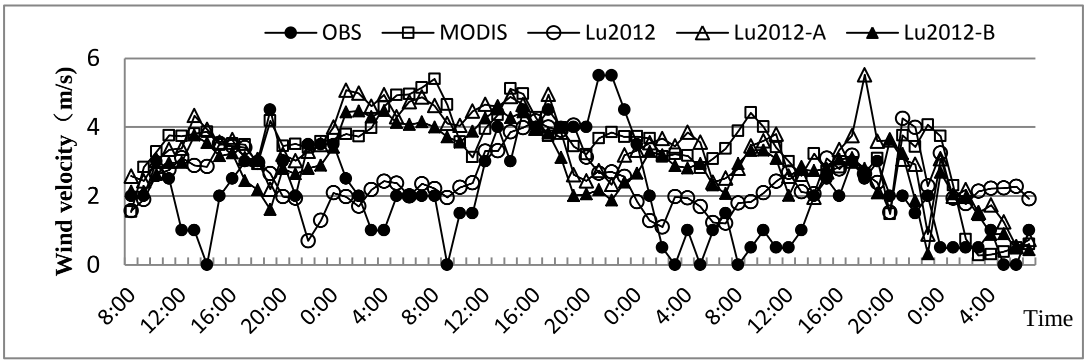


Fig.5 Comparison of wind velocity at 10 m height simulated in four experiments with observations

For wind velocity, all the simulation results are close to the observation data in daytime, Fig.5 compares the observed and modeled 10m height wind velocity.In general, become larger in the nighttime. On 1st and 2nd August, the distribution trends are similar between the simulation and observation .WRF simulation results cannot accurately reflect the observasion. It is caused by the model, although coupled with UCM model, still can not reflect the reality of the building influce on the wind environment.

3.2 Impact of urban expansion on UHI intensities

By comparing the simulations of the four experiments, the simulating capabilities on urban heat island can be further examined. Fig. 6 presents the evolution of the heat island intensity as simulated by the four experiments . The intensity of the heat island is calculated by the difference in temperature at the 2-m height between comparsion poin1 and comparsion poin2(in urban area). As shown by the observation, the UHI intensity is gradually increasing after the midday and becomes strongest at night, with the maximum temperature difference at more than 5℃,while it gradually decreases in the morning and even gets negative at noon. Though all the cases reproduce these characteristics of the UHI evolution except failure to depict the negative UHI on Aug.3rd and most time the modeled underestimate UHI intensity. Cases with UCM model have a higher capability to reproduce the UHI intensity on peak time but lower on other time than other experiments. Compared to the **Lu 2012-B**, **Lu2012-A** have a higher urban heat island intensity peak, which can own to anthropogenic heat release .

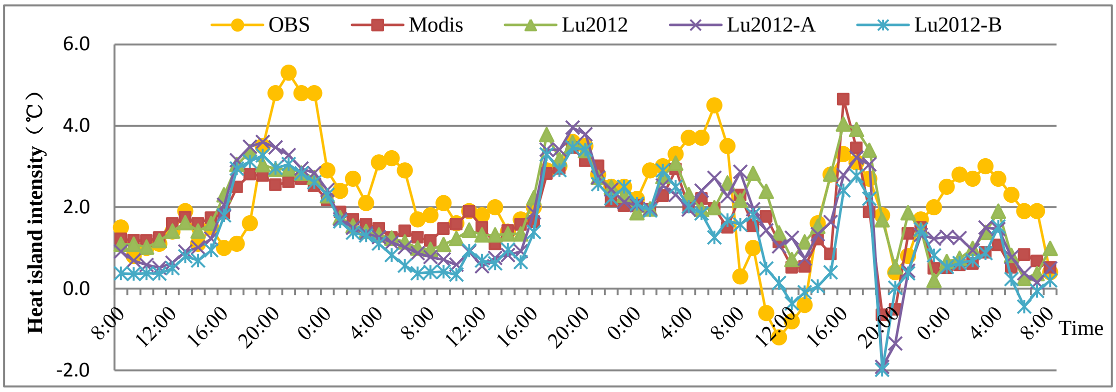


Fig.6 Heat island intensity of different experiments

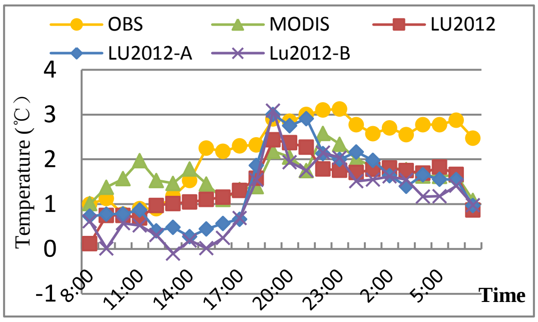


Fig.7 Diurnal cycles of the UHI intensities averaged over the simulation period

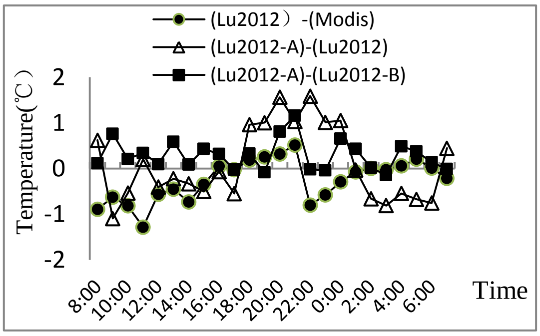


Fig.8 Daily range of averaged UHI intensities of different experiments

The diurnal cycles of the UHI intensities averaged over the simulation period is shown in Fig. 7. We can clearly found that all modeled cases have a better UHI intensity characteristics reproduction from 8:00 to 21:00, but a big gap in other time. The maximum UHI intensity for the 2-m temperature occurred at approximately 2000 LST around sunset, with the value of approximately 3.0 °C. Both the cases of Lu2012-A and Lu2012-B have a higher maximum UHI intensity, which more agree with the observation. All the modeld cases depict a big underestimat at night time than observation.

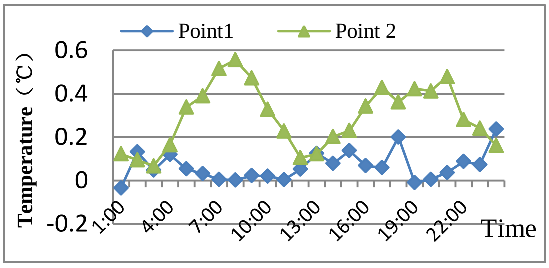


Fig.9 Averaged diurnal range of 2-m temperature between **Lu2012-A** and **Lu2012-B**

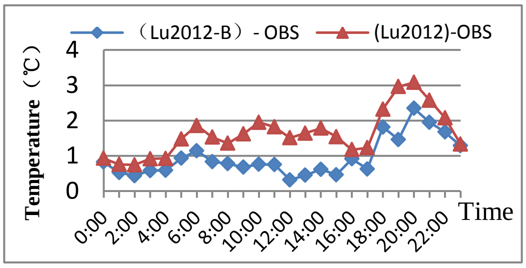


Fig.10 Averaged diurnal range of 2-m temperature at point 2

Fig.8 show daily range of averaged UHI intensities of different experiments. Differences between the **Modis** and **Lu2012** indicate the total effects of different land use data on UHI intensity, and great differences are shown when using different land use data .The contribution of UCM on the UHI can be assessed by the difference between the **Lu2012** and **Lu2012-A**. The maximum diurnal cycles of the UHI intensities occurs at 19:00 suggest that the relative contributions to the maximum UHI intensities by coupled with UCM is 0.57℃. Among the day, the maximum contributions to UHI intensities is 1.58℃ at 20:00. The Fig.10 depicts that WRF coupled UCM model simulated the temperature more accurate than the observation.

The AHR is an important fatory influencing the modeling of UHI effects. The contribution of AHR to the UHI effect can be assessed by the difference between the **Lu2012-A** and **Lu2012-B**. They have the similar maximum diurnal cycles of the UHI intensities，but most time，the UHI intensities of **Lu202-A** larger than **Lu2012-B**, and the most value is 0.8℃ at 19:00, when there is a maximum AHR in Guangzhou. Fig.9 reveals that AHR regularly affects the 2-m temperature at urban area and can be up to 0.6℃ at 8:00 and 19:00. The AHR used in this study and its diurnal variation are based on default values in the UCM and may differ from actual AHR in Guangzhou.

4.Summary and conclusions

Using the WRF coupled UCM model, the UHI over Guangzhou in the summer of 2012 was simulated.Different runs with Defult Modis land use data and extracted land use data from the RS data of year 2012 were performed. Two other urbanization scenario runs were designed to assess the relative contributions of UCM and anthropogenic heat release to the UHI in the present study and the following conclusions can be drawn:

(1)The experiments with different land use data have a significant impact on the WRF simulation result. The land use data extracted from the RS data of year 2012 can have a encouraging agreement with observations though the maxmum tempreature a little larger than the observation.

(2) The experiments with UCM model have a better simulation of the evolution of temperatures at the height of 2 m in urban areas than without couple UCM model. The experiment Lu2012-A which with new land use data and coupled with the UCM model has a lowest mean-root-square-error, which reveals that it is best in reproducing the variation of temperature.

(3) The experiments with UCM model simulated nocturnal heat island is the most intense, around 3° C. It can more useful in capturing the temporal distribution of the UHI, which is strongest at night, while it gradually decreases in the morning and even gets negative at noon.

(4) Comparisons among the results of four sensitivity runs showed that coupled the UCM model with classification of three urban land subcategories,and consideration of anthropogenic heat release respectively contributed 0.58°C and maximum 0.89 °C to the simulated UHI effects.

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