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A NUMERICAL STUDY ON THE INFLUENCES OF URBAN PLANNING AND CONSTRUCTION ON THE SUMMER URBAN HEAT ISLAND IN THE METROPOLIS OF SHENZHEN

ZHANG Xiao-Li (张小丽)[1], LI Lei (李　磊)[1], DU Yan (杜　雁)[2], JIANG Yin (江　崟)[1], FANG Xiao-yi (房小怡)[3], LI Mei (力　梅)[1], CHEN Yuan-zhao (陈元昭)[1], BAI Yu-jie (白玉洁)[4]

(1. Meteorological Bureau of Shenzhen Municipality, Shenzhen 518040 China; 2. Urban Planning & Design Institute of Shenzhen, Shenzhen 518031 China; 3. Beijing Municipal Climate Center, Beijing 100089 China; 4. Guangdong Meteorological Training Centre, Guangzhou 510080 China)

Abstract: By means of the regional boundary layer model (RBLM), a study on the influences of the urban planning and construction on the summer urban heat island (UHI) in the metropolis of Shenzhen is performed. In the study, the current summer UHI distribution, the influences of the increasing high-density construction and the energy consumption on the summer air temperature distribution, and the influences of the urban ventilation corridor on the summer air temperature distribution are numerically analyzed. Some conclusions are drawn in the light of the study: (1) The summer UHI is more obvious in day time than that in night time in the summer of Shenzhen, and the maximum values of UHI intensity in the day time appear in the areas with high-density construction, which are located in Nanshan, Futian and Luohu and western Bao′an districts. (2) The increase of construction density and energy consumption in the urban area will lead to the increase of temperature near the ground, and the increase of temperature at nighttime is more obvious than that at daytime. (3) The ventilation corridor can effectively reduce the UHI intensity and can be taken as a method to eliminate the negative climatic effect caused by the increase of high-density construction and energy consumption in the future.

Key words: urban heat island; numerical simulation; Shenzhen

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1 INTRODUCTION

The urban heat island (UHI) is a phenomenon of temperatures being higher in the urban area than in the neighboring countryside. Ever since the discovery in 1818 of significant UHI in London by Howard[1], a British scientist, the issue has been one of the hot topics in atmospheric sciences. Since the 1980s, research on UHI has been conducted in China that featured Beijing as a case (Qu et al.[2]; Zhou et al.[3]). Pioneering study was performed that centered on the UHI issue of Shanghai (Zhou[4]). Due to their unique status in China, Beijing and Shanghai are the focus of concern in much of the UHI work in China[5-10]. Additionally, other Chinese metropolis, like Xi'an and Chongqing, were also, one after another, studied for the UHI effect.

For a city, a reasonable overall planning is contributing positively to improving its own climate environment. Therefore it has scientific and realistic implications to study the relationships between urban planning and the UHI[13]. The urbanization of Shenzhen over a 30-year period is the fastest case of its kind in the world, thus granting the work on the local UHI significant implications of science. Against the background that increasing shortage of land resources has made high-density construction inevitable, the study on Shenzhen's UHI is much more realistic for urban planners and constructors to

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Biography: LI Lei, Ph. D., associate professor, primarily undertaking research on boundary-layer physics and urban climate research.
Corresponding author: LI Lei, e-mail: chonp@163.com

formulate reasonable schemes to mitigate its adverse effects.

There are now some methods that employ observations to study the UHI. Having analyzed how air temperature is affected by the environment of observation using single-station data, Zhong[14] pointed out that UHI has already made impacts on Shenzhen. With air temperature measurements from 19 automatic weather stations in 2004, Zhang et al.[15] studied the city's spatial distribution, seasonal variation and diurnal range of the UHI. Song et al.[16] summarized the spatial morphology of UHI in this metropolis. All of the above work helps broaden the knowledge about the issue.

Compared to methods like the analysis of observational data and remote-sensing data, numerical modeling, which yields data that are high in both time and space resolution, is the most convenient and economic means to address the issue of UHI. Besides, as the conditions for experiments are controllable, numerical modeling is more suitable for scenario projection that deals with the effect of various schemes of urban planning on the UHI. In view of it, this paper, on the basis of previous work, designs three sets of numerical modeling schemes to study the present situation of UHI in the summer of Shenzhen and to predict the changes potentially resulting from increased energy consumption and construction density in the future. The current work also presents a quantitative assessment of the effect of ventilation corridors in releasing summertime UHI.

2 METHODS OF RESEARCH

2.1 *Brief introduction to model*

In the current study, numerical modeling is used in conjunction with scenario projection and analysis. The model used, RBLM, is a regional boundary-layer model provided by Fang et al. as a multi-scale modeling system for cities. Being three-dimensional and ageostrophic, this model uses a set of governing equations for the atmospheric motion that include Reynolds average[17]. It also introduces a parameterization scheme for urban canopy that can describe the kinetics and thermodynamics of the urban underlying surface. For the kinetics, the RBLM incorporates the terms of damping and perturbation arising from urban buildings into the equation with u and v components and the equation of turbulence energy:

$$F_u = -\frac{1}{2}\eta C_d A(z) u (u^2 + v^2)^{1/2} \tag{1}$$

$$F_v = -\frac{1}{2}\eta C_d A(z) v (u^2 + v^2)^{1/2} \tag{2}$$

$$F_E = -\frac{1}{2}\eta C_d A(z) v (|u|^3 + |v|^3) \tag{3}$$

$$F_\varepsilon = \frac{3}{4}\frac{\varepsilon}{E}\eta C_d A(z) v (|u|^3 + |v|^3) \tag{4}$$

where F_u, F_v, F_E and F_ε are the u and v component, turbulence kinetic energy E and a term of disturbance added to the predictive equation for turbulence dispersion ε, respectively. $A(z)$ is the index of the surface area of all urban buildings, which is defined as the ratio of windward surface of the buildings to the air volume inside a grid, η the proportion of building area inside each of the grids, and C_d the drag coefficient that takes an empirical value of 0.4.

For the kinetics, RBLM takes into account the heating effect of anthropogenic heat release on the land surface and the near-surface atmosphere, whose concrete forms are presented in Eqs. (5) and (6):

$$\frac{\partial \theta'}{\partial t} + u_j \frac{\partial \theta'}{\partial x_j} = \frac{\partial}{\partial x_j}\left[k \frac{\partial \theta'}{\partial x_j} \right] + Q_{anth} \tag{5}$$

$$\frac{\partial T_S}{\partial t} = C_T (R_n - H - LE + Q_{anth}) - \frac{2\pi}{\tau}(T_S - T_2) \tag{6}$$

where θ is the geopotential temperature of the atmosphere, T_s the land-surface temperature, R_n the net radiation received by the land surface, H the sensible heat, LE the latent heat, C_T the thermal coefficient, T_2 the temperature deep inside the soil, and Q_{anth} the anthropogenic heat. According to Fang et al., BRLM is capable of simulating urban boundary layers with results well consistent with the observations[17].

2.2 *Brief introduction to the modeling scheme*

The domain to be simulated in this study is composed of the entire region administered by Shenzhen and part of the neighboring Dongguan, Huizhou and Hong Kong. The urban area inside the simulated domain is shown by the purple blocks in Fig. 1. With its centre passing the point (22° 38′ 47.22″ N, 114° 10′ 30.25″ E), this area is 100 km across from east to west and 50 km in length from north to south, horizontally resolvable at 1 km× 1 km. It is vertically layered into 33 levels. The vertical grid interval is 50 m on the bottom level, increasing by a ratio of 1:1.2 for the levels upward without exceeding 200 m at most. The terrain being simulated is shown in Fig. 2. Data from a surface observation station at Caiwuwei and soundings from Hong Kong are the source of meteorological elements used to generate the background field of objective analysis. Besides, the observations from another station at Xiaowutong are compared with the simulations for analysis. The locations of the two stations are indicated by two blue five-pointed stars next to letters A and B in Fig. 2. The duration of simulation covers 2000 Beijing Standard Time (BST) June 22 to 0800 BST June 24, 2007. or a period of 36 hours. The time step is 2 seconds. The results for the latter 24 hours of the modeling were selected for analysis.

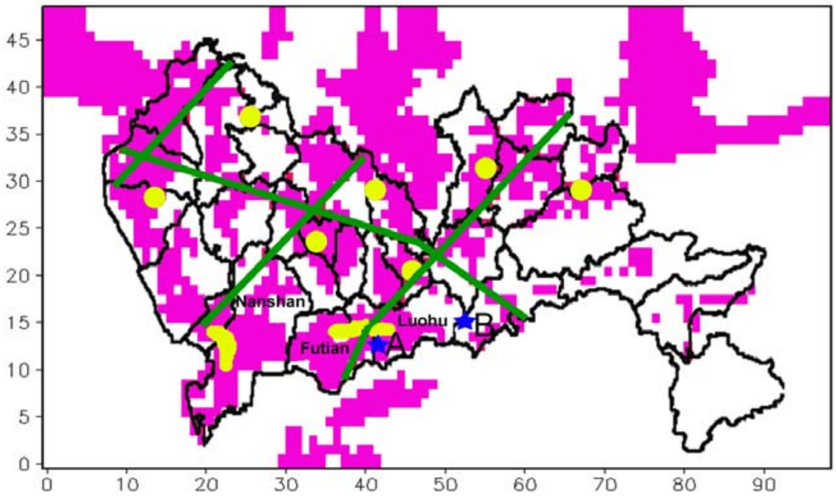

Fig. 1. Schematic diagram of the modelling scheme.

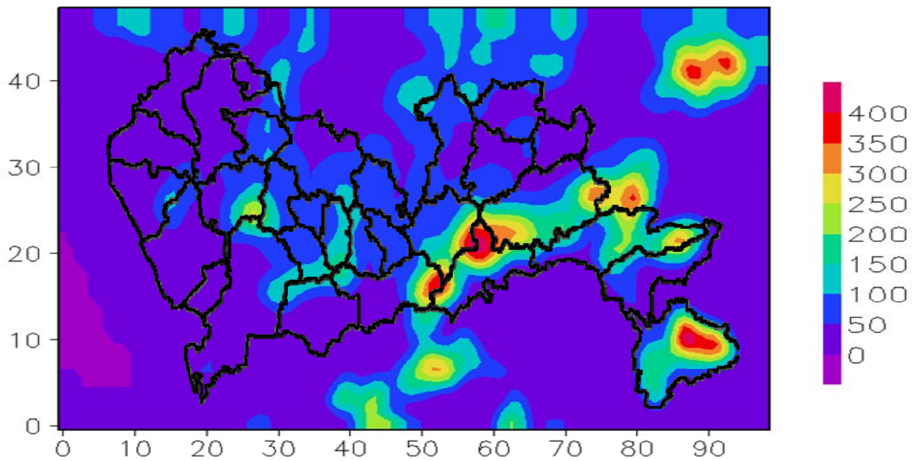
Fig. 2. Distribution of the terrain within the simulated domain (unit of altitude: m).

Three sets of schemes were designed for the modeling to reflect the different phases of urban planning and construction in Shenzhen. Scheme 1 is a "status quote modeling" that takes into account the basic patterns of urban construction at present (with 2005 as the base year). Scheme 2 is a "predictive modeling" that addresses the possible effects of high-density urban construction. Scheme 3 is an "adjustment modeling" that works on adding "ventilation corridors" to densely-built urban areas to mitigate the effect of UHI.

For scheme 1, the coverage data of completed urban construction are provided by the Planning and Design Institute of Shenzhen. They include existing urban areas of both Shenzhen and neighboring metropolises. Based on the current data of urban construction and socio-economic development, this scheme studies the density of construction above Shenzhen's underlying surface on a district basis. As the districts of Futian, Luohu and Nanshan are densely constructed, their average height of buildings takes 60 m, three times as high as that of the other districts and the average intensity of anthropogenic heat release is set at 140 W/m^2 for the three districts while that of the other districts is assumed to be around 70 W/m^2.

For Scheme 2, a modeling for scenario projection, assumptions are made that energy consumption will be up by 33% and so will the anthropogenic heat release in all of the completed parts of the city. It is also assumed that a number of urban centers have also been completed (as indicated by the yellow blocks in the figure) and the average height has increased to 80 m because of measures of high-density development. Comparisons of Scheme 2 with Scheme 1 can be used to study the effect of increased energy consumption and construction intensity on the distribution of near-surface air temperature in the city.

Scheme 3 is actually an adjustment based on Scheme 2 in which ventilation corridors are set up (as indicated by the green lines in Fig. 1). As shown in the climatological data over the past 50 years, the wind direction with maximum frequency in Shenzhen is NE, followed by E and ESE. The corridors for ventilation are therefore set to be going northeast-southwest and northwest-southeast. Being 1 km in width, the corridors are covered with grass in numerical modeling. Comparisons of Scheme 3 with Scheme 2 can be used to assess the role of ventilation corridors on the mitigation of UHI effects.

3 SIMULATIONS AND ANALYSIS

3.1 *Scheme 1*

Figure 3 gives the distribution of air temperature simulated by Scheme 1 that is 1.5 m above ground surface at 1200 BST at midday and 0000 BST at midnight, respectively. It shows that the UHI phenomenon exists over all land area of Shenzhen during either daytime or nighttime, as evidenced by much higher temperature in the completed urban areas than the uncompleted ones. In this study, the UHI intensity is defined as the difference at the same above-sea-level heights over land surface between the maximum temperature of completed urban areas and minimum temperature of the countryside, which is similar to the urban heat island determined in Zhang et al.[15] During daytime in summer, the UHI intensity can be as high as 4 °C in the western part of the metropolis that is mildly above sea level, a result that bears similarity to that of Zhang et al. with AWS statistics. High-value cores of UHI distribute over Nanshan, Futian and western Bao’an where temperatures are more than 33 °C but are between 31 °C and 33 °C in other districts that also have significant heat-island phenomenon. For these districts, correspondingly, the UHI intensity is between 2–4 °C. Compared to the UHI intensity of Hong Kong determined by Wu et al.[18], the numerals of UHI obtained by our modeling are roughly comparable to the annual mean UHI (2.2–2.5 °C) for Hong Kong but smaller than its absolute value of the maximum (4.5–4.9 °C). Still, nighttime temperatures are higher in the completed urban areas than in the woods, with cores of high values (more than 27 °C) located in western Nanshan, western Luohu and western Bao’an. During the night, however, the UHI phenomenon is not as significant as during the daytime as temperatures are also relatively high over bodies of water and surrounding sea surface.

To verify the simulating capabilities of the model, Fig. 4 gives the distribution of surface temperature as retrieved from remote-sensing data of Shenzhen for November 10, 2006. Comparisons of the distribution of air temperature, determined from numerical modeling within the area of Shenzhen (Fig. 3a), with the distribution of surface temperature, obtained by retrieving remote-sensing data (Fig. 4), show that they have highly consistent thermodynamics and indicate cores of high temperature in the completed urban zones of Nanshan, Futian, Luohu, Bao’an and Longguang. It is a sufficient proof that the RBLM model is well capable of reflecting the atmospheric thermodynamics of urban Shenzhen.

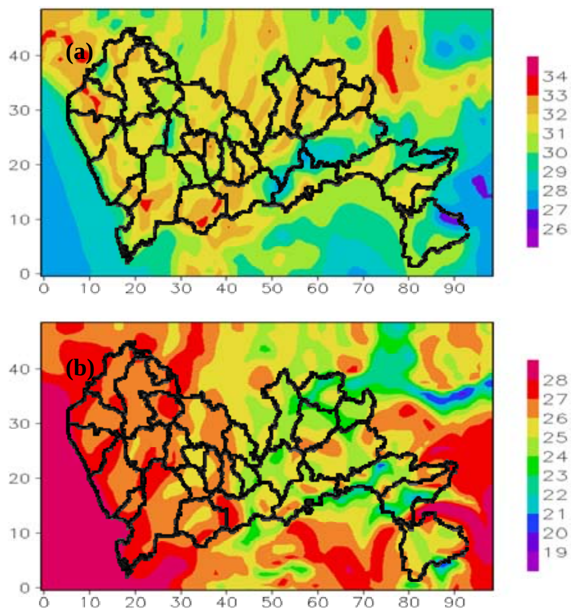

Fig. 3. Distribution of near-surface air temperatures as determined with Scheme 1 (Unit of temperature: °C). a: 1200 BST midday; b: 0000 BST midnight.

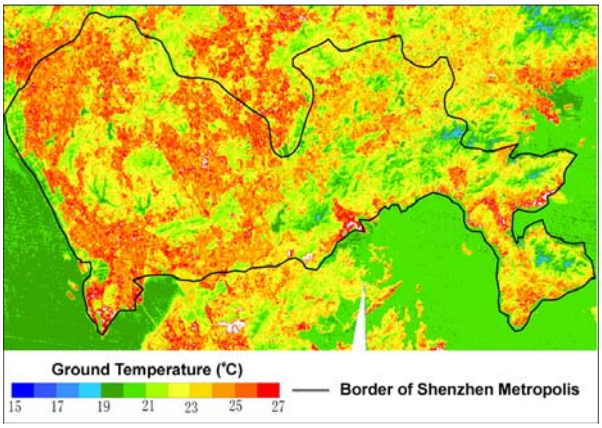

Fig. 4. Distribution of land-surface temperatures determined from remote-sensing data retrievals.

To further verify the reliability of simulated results, Fig. 5 gives the comparisons of simulated air temperatures and the observations between the stations at Caiwuwei and Xiaowutong. The RBLM-simulated results generally coincide with the observations because they give reasonable modeling of the near-surface temperatures with regard to the trends of diurnal and nocturnal variations. It is noteworthy, however, that the simulated values of air temperature for both of the stations are lower than the observations, especially for Caiwuwei, for which the difference is about 2 °C. It suggests that the model is somewhat incapable of simulating the distribution of air temperature in the layer near the surface for some sections of the night hours.

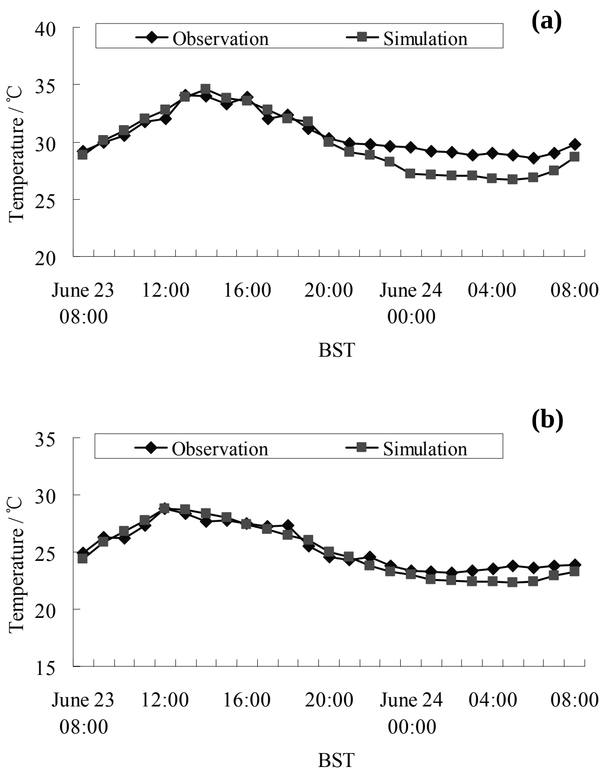

Fig. 5. Comparisons of temperatures simulated with Scheme 1 and those observed at 1.5 m above ground. Unit of temperature: °C. a: Station Caiwuwei; b: Station Xiaowutong.

3.2 *Scheme 2*

Since the opening-up and reform in 1978, Shenzhen has experienced rapid urbanization. High-density construction has become a strategy of development for some parts of the city in order to make the most use of space from limited land resources, increasing land-use efficiency by raising construction intensity per unit of land area. For this purpose, Shenzhen undertakes, in its fresh round of planning, measures of constructing multiple centers to add a number of central districts throughout the metropolis and to implement high-density construction. As demands for energy consumption will increase in the future, this work undergoes scenario projections by assuming a 1/3 increase in energy consumption. Scheme 2 is formulated as follows by summarizing the points above.

The results of Scheme 2 simulations are used to study the variation of near-surface temperature relative to Scheme 1. Fig. 6 gives the difference in the near-surface temperature between Scheme 1 and Scheme 2.

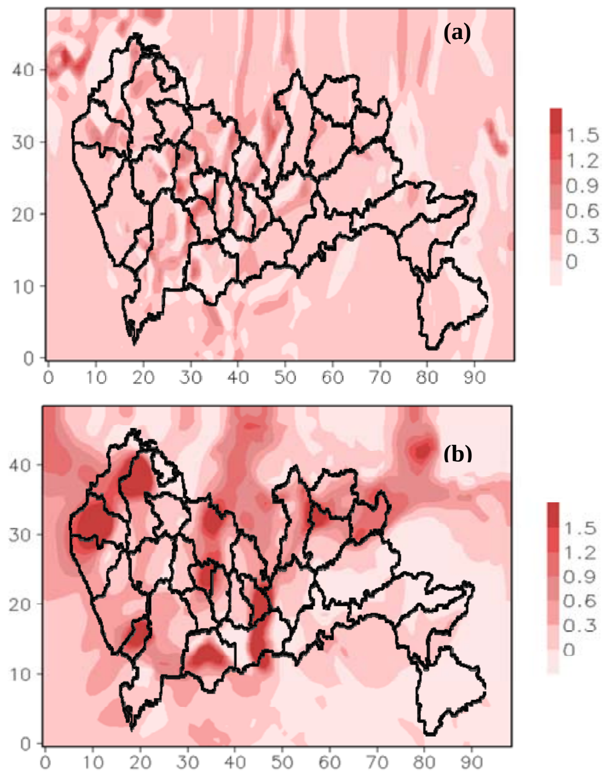

Fig. 6. Differences of the near-surface temperatures determined by subtracting Scheme 1 from Scheme 2 (unit: °C). a: 1200 BST midday; b: 0000 BST midnight.

As shown in Fig. 6, as energy consumption increases in Scheme 2, the near-surface temperature may rise over extended areas in the summer with a larger magnitude at night than during the daytime. During the daytime, the temperature rise is between 0-0.6 °C in most of the area and can reach about 1.2 °C in some areas around the central districts that are densely built in the new plan. The temperature rise is even more evident at night, especially in areas surrounding the newly added central districts, where the amplitude is as much as 1.5 °C or more. This would escalate the UHI intensity in this part of the city that is completed. The simulations of Scheme 2 shows that the increased high-density construction and energy consumption, probably taking place in the future, could result in the rise of local temperature in Shenzhen, inevitably worsening the high-temperature weather in the summer. Meanwhile, the increase of local temperature will stimulate the consumption of power for air-conditioning to increase energy consumption. Such runaway cycle will challenge efforts of saving energy, reducing emissions and improving the inhabiting environment of people.

3.3 *Scheme 3*

As shown in some studies, the addition of green land, ecological corridors and ventilation corridors help improve the local environment of cities and reduce the UHI intensity[19]. Scheme 3 proposes the set-up of ventilation corridors in Shenzhen and gives quantitative assessment, through sensitivity experiments, of their role in adjusting urban climate.

The results of Scheme 3 simulations are used to study the variation of near-surface temperature relative to Scheme 1. Fig. 7 gives the difference in the near-surface temperature between Scheme 2 and Scheme 3. It shows that the addition of ventilation corridors has significant effects on reducing the near-surface air temperature of summer. Because of the corridors, the diurnal temperature has a drop of 0–0.1 °C over most parts of the city, but more than 0.5 °C in the northwestern corner and central part in which there are ventilation corridors. The adjusting effect is more significant nocturnally because it reduces the temperature by more than 0.9 °C. Comparisons of Scheme 3 with Scheme 2 show that reasonable planning measures, such as the setting-up of ventilation corridors, can still help release some of the adverse climatic environment effects brought about by urban development, even when adequate high-density construction and further increases of energy consumption are considered strategies needed to be taken in future development.

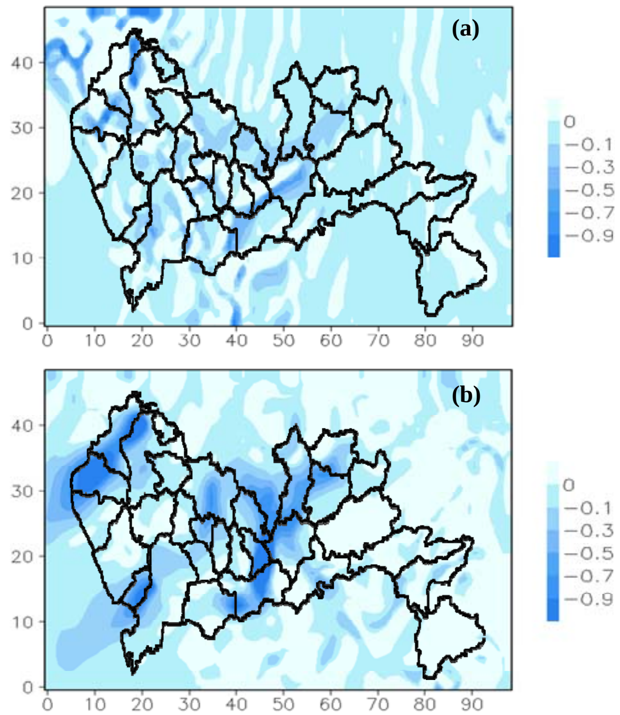

Fig. 7. Differences of the near-surface temperatures determined by subtracting Scheme 2 from Scheme 3 (unit: C). a: 1200 BST midday; b: 0000 BST midnight.

3.4 *Comparisons of vertical profiles of temperatures*

To compare the effect of different schemes on the vertical profiles of temperatures within the boundary layer, Fig. 8 compares the vertical profiles of temperatures determined with different schemes for heights below 1000 m within the modeling domain where *x*=36 km and *y*=27 km.

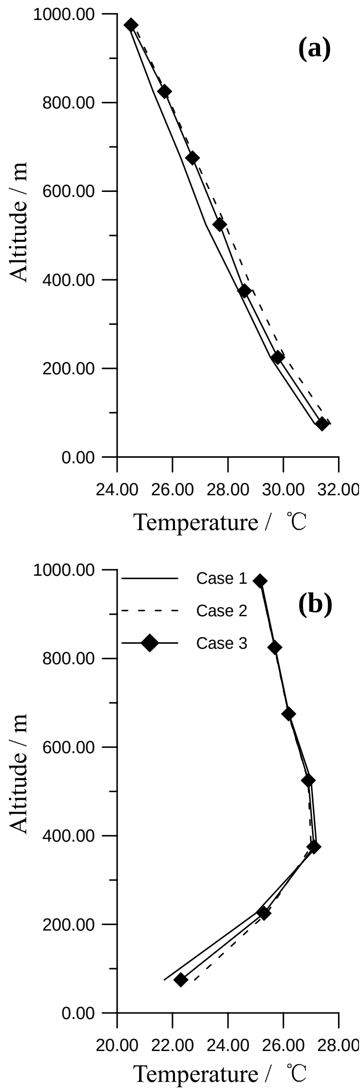

Fig. 8. Vertical distribution of air temperatures simulated with the three schemes. a: 1200 BST midday; b: 0000 BST midnight.

As shown in Fig. 8a, the vertical profiles of temperatures simulated with the three schemes all vary in a similar way, though affecting the vertical distribution of the near-surface temperature to some extent. In the diurnal hours of the summer, the influence of increased construction density and anthropogenic heat release can be felt as high as 1000 m above ground. Temperatures simulated with Scheme 2 and Scheme 3 are much higher than with Scheme 1 at all respective heights. In Scheme 3, to which ventilation corridors are added, simulated temperatures are much lower than in Scheme 2 at heights below 700 m, suggesting that their adjustment may reach the middle and lower portions of the boundary layer. In the nocturnal time of the summer, however, the effect of the construction density and anthropogenic heat release on temperatures are mainly confined to the inversion layer below 400 m, though with larger differences in simulated near-surface temperatures than during the daytime.

4 CONCLUSIONS

With a regional boundary-layer model, RBLM, this work designed three sets of numerical modeling to study the impact of the urban planning and construction in Shenzhen on summertime heat-island effects.

(1) In Shenzhen, the phenomenon of urban heat islands exists in summer with the effect more obvious during the day than the night. In terms of the UHI intensity defined in this work, the area just above sea level in western Shenzhen can be as high as 4 °C. A number of high-temperature centers occur in the completed parts of the city, mainly in Nanshan, Futian, Luohu and western Bao'an.

(2) The increased construction intensity and energy consumption will result in the rise of near-surface temperatures over large portions of Shenzhen in summer, much more so during the night than during the day. It will worsen, to some extent, extreme summertime heat there.

(3) To a mild extent, the setup of ventilation corridors can reduce the UHI intensity and relieve the summer heat, more evidently during the night and by more than 0.9 °C in some locations near the corridors.

(4) In terms of physical mechanisms, the circulation of UHI is not conducive to the dissipation of pollutants. The increase of the concentration of pollutants (especially the aerosols) will influence the intensity of UHI. The present version of the RBLM model is incapable of describing the radiative effect of aerosols (and there is a lack of observations of concentration of aerosols observed vertically in Shenzhen), probably leading to the errors between the simulated results and observations. Generally, though, this regional boundary-layer model gives reasonable description of the relationships between the urban construction and UHI in the area of Shenzhen and can be used for assessment in related fields.

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