Further Development of the Regional Boundary Layer Model to Study the Impacts of Greenery on the Urban Thermal Environment

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ABSTRACT

A forest canopy model is developed and coupled into the Regional Boundary Layer Model (RBLM) to fully consider the vertical structure of tree morphology. Instead of a slab surface model formerly used to represent trees in RBLM, the new version allows refinement of the radiation budgets as well as sensible and latent heat fluxes and, hence, more precise simulation of the thermal impacts of tree plantings on urban meteorological behavior. By applying this new version of RBLM, sensitivity tests are conducted to explore the potential impacts of different greenery scenarios on the thermal environment in an eastern Chinese city, Suzhou, during hot summer days. Greenings, both tree planting and grass surfacing, are beneficial in cooling the ambient air temperature. In general, tree planting is more beneficial than grass surfacing with the same coverage. In terms of surface energy balance, with tree coverage increasing from 0% to 20%, and then to 40%, the average surface net radiation fluxes at noon (1200 LST) are 591, 512, and 421 W m⁻², respectively. Correspondingly, the Bowen ratio is reduced from 8.78 to 1.20 and then to 0.43 as result of the redistribution of solar energy absorbed at the ground. The cooling effect of trees is more significant at noontime and can remarkably lower the daily maximum air temperature in urban areas. The cooling effect of urban greenery increases with its coverage. Using the study results, a tree coverage of around 40% may be a feasible and optimized urban greenery scheme.

1. Introduction

Urbanization quickly spreads all over the world and leads to rapid economic development. However, this may also cause many problems for city dwellers. One of the most prominent and intensively studied problems, the urban heat island (UHI), has caused thermal heat stress and even increased health risks, especially during hot summer months. For example, heat waves had devastating impacts in Chicago, Illinois, in 1995 (Changnon et al. 1996; Semenza 1996). An estimated 15 000 excess deaths were attributed to the heat-wave event across France in August 2003 (Fouillet et al. 2006). To make things worse, several studies have predicted an increasing tendency of the intensity and frequency of heat waves and indicated that urbanization might be one of the reasons causing heat-wave increases over urban areas (Meehl and Tebaldi 2004; Meng et al. 2010). Li and Bou-Zeid (2013) investigated the interactions between UHIs and heat waves. They suggested that the UHI effect is amplified during the heat-wave period because of the lack of vegetation and surface moisture in urban areas. Thus, there is an urgent demand to evaluate and execute strategies that could mitigate the urban heat island effects.

Considering the recreational and aesthetic functions of urban inhabitants, planting more vegetation has widely been suggested as a promising mitigating measure (Ca et al. 1998; Ashie et al. 1999; Tong et al. 2005; Yu and Hien 2006). Air temperature reductions of up to 3–4 K at noontime that are attributable to trees were observed during summer (Bernatzky 1982; Shashua-Bar and Hoffman 2000; Potchter et al. 2006), and reductions...
of up to 2 K were observed in association with urban lawns (Bonan 2000; Spronken-Smith et al. 2000) and green roofs (Takebayashi and Moriyama 2007; Alexandri and Jones 2008).

Although the cooling effect of greenery has been observed by many researchers, especially for hot climates, studies that quantify the possible effects of different greenery scenarios (including various vegetation coverage and greenery types) on the urban thermal environment are relatively lacking. Shashua-Bar et al. (2011) conducted an observational experiment in Israel to test the distinct effects of trees and grass on an outdoor thermal environment in a hot-arid region. Considering the obvious difficulties involved with on-site measuring of the impact of different greenery scenarios under the same conditions, research efforts addressing this issue have had to resort to numerical simulations.

So far, several urban canopy models with varying complexities have been developed for urban meteorological modeling scenarios (e.g., Masson 2000; Kusaka et al. 2001; Hamdi and Masson 2008; Kawai et al. 2009). However, most of these models consider building “canyons” only, ignoring the vegetation planted within urban street canyons. In fact, vegetation has always been an important component of the urban landscape; for example, in many regions of America, tree canopy coverage can reach up to 20%–40% on a city-wide basis (Oke 1989). Moreover, the canyon vegetation can have a notable influence on the urban surface temperature and ambient air temperature and humidity (Robitu et al. 2006); modifying the surface energy balance over urban areas. Thus, in the field of urban meteorological modeling, a proper representation of the microclimatic effect of vegetation opens opportunities to study the urban climate with better accuracy (Lee and Park 2008). Furthermore, in the International Urban Balance Models Comparison Project conducted by Grimmond et al. (2010, 2011), the authors clearly state that taking vegetation cover into account significantly improved model performance. Not many models have considered the role of vegetation in affecting urban climate. Shashua-Bar and Hoffman (2002, 2004) included the thermal impacts of shade trees in their Green Cluster Thermal Time Constant (Green CTTC) model, derived from solar radiation exchange. Lee (2011) has developed the Vegetated Urban Canopy Model by including the presence and effects of trees and grass in the radiative, dynamic, and energetic calculations.

At present, the incorporation of vegetation into the modeling of an urban surface is realized mainly through two different approaches: one is the so-called tile approach. That is, representation of the surface heterogeneity by gathering distinct surface classes within a grid into homogeneous “tiles” in a “mosaic” (Koster and Suarez 1992). Different types of underlying surface within a grid do not interact with each other until the first atmospheric layer of a mesoscale model. The total fluxes are calculated by taking an area-weighted average of different surface types within each grid (e.g., Essery et al. 2003; Best et al. 2006). The other is the integrated approach; that is, vegetation is directly integrated into the urban canyon modeling (e.g., Lee and Park 2008; Lemonsu et al. 2012). Elaboration on the tile and integrated approaches can be found in Grimmond et al. (2010).

The above-mentioned two approaches for incorporating vegetation mainly differ in whether or not there are interactions between the “artificial” and “vegetated” fractions. Each of the approaches has its own merits. The tile approach takes advantage of conventional land surface schemes, which have a wide range of vegetation categories (e.g., Essery and Clark 2003). This approach is convenient for exploring the potential impacts of different urban greenery schemes (e.g., different vegetation classes or different levels of vegetation coverage) by simple modification of some characteristic parameters or the area fractions of vegetation. As for the integrated approach, it is the most physically realistic because it directly takes into account the interactions between artificial and vegetated areas. Given the purpose of the present study, the former was employed to represent the role of greenery in urban areas in our simulation.

The first objective of this study is to introduce an updated version of the Regional Boundary Layer Model (RBLM) to increase our understanding of ambient temperature variation induced by tree planting within urban areas; and the second is to evaluate the potential impacts of different greenery schemes on an urban thermal environment using the new model. For this purpose, a forest canopy model is coupled with RBLM in order to fully consider the vertical structure of tree morphology instead of a slab-surface approach, as has been previously used to represent trees in the RBLM. This allows refinement of the radiation budgets as well as sensible and latent heat fluxes and, hence, more precise simulation of the thermal impacts of tree plantings (e.g., gardens, backyards, and roadside trees) on urban meteorological conditions. This work is a meaningful scientific endeavor for the improvement of urban climate modeling, particularly on realistic representations of urban green areas, and will allow urban planners to identify more accurately the optimized greenery types and amounts for a better urban living environment.

The model descriptions are presented in the next section. A validation of the coupled model is shown in section 3. Details of several simulated results and some discussion are given in section 4. Conclusions are summarized in section 5.
2. Model descriptions

a. The RBLM

RBLM is a regional-scale (from a few kilometers to a few hundred kilometers) meteorological and atmospheric dispersion numerical weather prediction model with a three-dimensional (3D) nonhydrostatic turbulence closure scheme, which was developed for use in urban meteorological modeling. The original version of the RBLM is described in detail by Chen et al. (2009). This model has been used in several studies about urban meteorological issues (Xu et al. 2002; Jiang et al. 2007; Chen et al. 2009).

In the new version of the RBLM, the land-use type of the underlying surface is categorized into 15 classes, and urban is one of them. For all 14 of the other classes (grass, water, soil, farmland, etc.), the land surface process is treated by the adoption of the two-layer soil-vegetation scheme (Pleim and Xiu 1995). For urban underlying surface, it is noteworthy that the real urban surface is covered by varying proportions of buildings, roads, lawns, trees, water, and so on. Thus, a tile method was employed in the present study for realistic representation of subgrid heterogeneity within urban areas; that is, each urban grid is supposed to be composed of several subgrids. Each subgrid is categorized into the six most common urban classes, including street canyon, water, tree, grass, soil, and farmland. For street canyon, the land surface process is treated through the application of the Nanjing University Urban Canopy Model single-layer scheme (NJU-UCM-S) (Zhou et al. 2009); while for trees, a forest canopy model is newly incorporated into RBLM in this study for more precise simulation of the thermal impacts of tree plantings on urban meteorological behavior. These two models will be elaborated upon in the following sections. For the other four classes of subgrids, the two-layer soil-vegetation scheme (Pleim and Xiu 1995) is adopted. The final outcomes of each urban grid are calculated according to the relative area proportion of different classes within the grid. In this paper, these proportions are identified with the aid of a set of high-resolution (25 m × 25 m) land-use data obtained from Landsat-5 satellite observations.

Furthermore, the anthropogenic heat data adopted in this study are estimated using information about gross domestic product (GDP), energy consumption per unit GDP, land-use cover area, residence density, energy consumption of industrial plants, number of vehicles, and more, based on the Suzhou Statistical Yearbook 2011 (Statistics Bureau of Suzhou City 2011). According to our estimation [the estimation method can also be found in Chen et al. (2009)], the annual average anthropogenic heat flux is 48.4 W m⁻² in Suzhou City. The sources of anthropogenic heat flux are divided into four components: industry, transportation, residential, and metabolism sources. Figure 1 illustrates the diurnal variations and the total amount of the anthropogenic heat fluxes for each component. For the four distinct sources, the transportation, residential, and metabolism-related heat fluxes are directly added into the surface energy balance equation while the industry-related heat flux is assumed to influence the atmospheric potential temperature equation [all of these equations can be found in Chen et al. (2009)].

b. The Nanjing University Urban Canopy Model single-layer scheme

NJU-UCM-S is a single-layer urban canopy parameterization scheme that was developed for dealing with the land surface process over artificial surfaces within urban areas. This scheme is implemented in the RBLM for the improvement of radiation budgets as well as surface fluxes of heat and momentum within a real urban canyon geometry (i.e., representation of the radiation trapping effect within the urban canopy).

A detailed description of the NJU-UCM-S can be found in Masson (2000) and Kusaka et al. (2001). It is noteworthy that the NJU-UCM-S has participated in the International Urban Energy Balance Models Comparison Project conducted by Grimmond et al. (2010, 2011). In this project, the authors clearly display that the following characteristics will significantly improve the models’ performance: 1) including vegetation, 2) including anthropogenic heat, 3) using a single-layer or multilayer scheme instead of a slab one, and 4) consideration of urban morphology orientation. The NJU-UCM-S possesses the latter three features and its performance has been widely recognized in the field of urban land surface models (He 2006; Zhou et al. 2009; Grimmond et al. 2010, 2011).
c. The forest canopy model

As mentioned above, vegetation is an important component of urban street canyons. Canyon vegetation can have a great influence on surface energy balance as well as ambient temperature and humidity over an urban area. In the field of urban meteorological modeling, a proper parameterization of the urban vegetation is a prerequisite (Lee and Park 2008). The original version of RBLM is a useful tool for studying urban meteorological issues and has already been widely applied in several studies (as previously stated); however, it omitted the impacts of trees planted within urban areas. To address this issue, an updated version of RBLM is introduced for a realistic representation of urban surfaces in this study. Liu et al. (2005) first developed a forest canopy model to study the interactions between land surface physical processes and the atmospheric boundary layer over forest areas. With the coupling of the forest canopy model, the new version of RBLM allows refinement of the radiation budgets as well as sensible and latent heat fluxes and, hence, more precise simulation of the thermal impacts of tree plantings on urban meteorological conditions. More details about the calculation and evaluation process of this forest canopy model can be found in Liu et al. (2005). The tree species considered in this study belong to broadleaf forests, which are the most common vegetation type in Suzhou City. In addition, the new version of RBLM is capable of modeling different kinds of trees (coniferous, broadleaf, mixed forest, etc.) by simple modification of some characteristic parameters or the area fractions of vegetation. The main characteristic parameters associated with soil and vegetation are listed in Table 1, including tree height, leaf area density, emissivity for ground and vegetation, and so on. Note that the modeling study would certainly be more accurate if using in situ measured parameter values. However, in practice it is extremely difficult and beyond the objective of this study to measure the mean value of each parameter over Suzhou City. Hence, the parameter values used in this study are referred to in the relevant studies (Lalic and Mihailovic 2004; Lee and Park 2008; Huang and Ji 2010). This may limit the model performance and may need to be further addressed in future studies.

1) Radiation budget

The direct solar radiation received by a horizontal surface at the top of vegetation canopy is \( S_{down} \). The fraction of \( S_{down} \) absorbed by the vegetation to generate heat, \( S_v \) (W m\(^{-2}\)), is

\[
S_v = \text{Veg}(1 - \alpha_l)S_{down}, \tag{1}
\]

where Veg is the vegetation coverage and \( \alpha_l \) is the leaf surface albedo.

The other fraction that is absorbed by the ground to generate heat, \( S_g \) (W m\(^{-2}\)), is

\[
S_g = (1 - \text{Veg})(1 - \alpha_g)S_{down}, \tag{2}
\]

where \( \alpha_g \) is the ground surface albedo. The thermal effect caused by the shortwave reflections from ground and vegetation are neglected here.

The downward longwave radiation emitted from the atmosphere (W m\(^{-2}\)) is

\[
L_a = \varepsilon_a \sigma T_a^4, \tag{3}
\]

where \( \sigma \) is Stefan–Boltzmann’s constant and \( \sigma = 5.68 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \), \( T_a \) is the atmospheric temperature of the referenced layer (K), and \( \varepsilon_a \) is the atmospheric longwave radiation emissivity.

The upward (\( L_{v\uparrow} \)) and downward (\( L_{v\downarrow} \)) components of longwave radiation emitted by vegetation (W m\(^{-2}\)) are

\[
L_{v\downarrow} = L_{v\downarrow} = \text{Veg} \varepsilon_v \sigma T_v^4, \tag{4}
\]

where the subscript \( v \) means the vegetation subsystem, \( T_v \) is the average temperature of the vegetation (K), and \( \varepsilon_v \) is the vegetation emissivity.

The longwave radiation emitted by the ground (W m\(^{-2}\)) is

\[
L_g = \varepsilon_g \sigma T_{g_s}^4, \tag{5}
\]

where \( T_{g_s} \) is the surface temperature (K) and \( \varepsilon_g \) is the ground emissivity.

Neglecting the reflections of longwave radiation by vegetation and ground surfaces, the longwave radiations absorbed by vegetation \( L_{vin} \) (W m\(^{-2}\)) and the ground surface \( L_{gin} \) (W m\(^{-2}\)), respectively, are expressed as
\[ L_{\text{vin}} = \text{Veg}(L_a + L_g) \quad \text{and} \quad \]
\[ L_{\text{gin}} = (1 - \text{Veg})L_a + L_{\nu_1}. \]

Thus, the net radiation fluxes on vegetation \( R_{n_v} \) (W m\(^{-2}\)) and the ground surface \( R_{n_g} \) (W m\(^{-2}\)), respectively, are
\[
R_{n_v} = S_v + L_{\text{vin}} - (L_{\nu_1} + L_{\text{vin}}) \quad \text{and} \quad \]
\[
R_{n_g} = S_g + L_{\text{gin}} - L_g.
\]

2) VEGETATION SUBSYSTEM

Sensible heat flux of the vegetation canopy \( H_v \) (W m\(^{-2}\)) is
\[
H_v = h \text{Veg} \mu(z) \rho_a c_p (T_v - T_a) \frac{R_a}{R_a}, \quad \text{where} \quad \mu(z) = \mu_m (\frac{h - z_m}{h - z})^n \exp \left( \frac{h - z_m}{h - z} \right),
\]
where \( h \) is the vegetation height (m), \( \rho_a \) is the air density (kg m\(^{-3}\)), \( R_a \) is the aerodynamic resistance for the leaf surface (s m\(^{-1}\)), and \( \mu(z) \) is the leaf area density (m\(^{-1}\)).

The aerodynamic resistance of the leaf surface \( R_a \) (s m\(^{-1}\)) can be estimated from
\[
R_a = \frac{1}{C_f V_a},
\]
where \( V_a \) is the surface wind velocity (m s\(^{-1}\)) and \( C_f \) is the conductivity coefficient of the vegetation, which can be calculated as (Deardorff 1978)
\[
C_f = 0.01 \left( 1 + \frac{0.3}{V_a} \right).
\]

The latent heat flux of the vegetation canopy (W m\(^{-2}\)) is
\[
\text{LE}_v = \lambda \int_0^h E_v dz.
\]

where \( \lambda \) is the latent heat of vaporization of water, \( \lambda = 2.5 \times 10^6 \text{ J kg}^{-1} \), and \( E_v \) is the moisture flux per unit length on the vegetation surface (kg m\(^{-3}\) s\(^{-1}\)), which is given by
\[
E_v = \text{Veg} \mu(z) \frac{q_{\text{sat}}(T_v) - qa}{R_a}.
\]

where \( q_{\text{sat}}(T_v) \) is the saturation specific humidity (kg kg\(^{-1}\)) when the surface temperature is \( T_v \), \( qa \) is the atmospheric vapor pressure (Pa), and \( R_a \) is the stomatal resistance of the vegetation (s m\(^{-1}\)), which can be estimated as
\[
R_a = R_{\text{min}} F_R F_T F_v F_\phi,
\]
where \( F_R, F_T, F_v, \) and \( F_\phi \) are, respectively, the adjustment factors for the solar radiation, leaf temperature, vapor pressure deficit, and soil water potential (Avissar and Mahrer 1988; Park 1994) and \( R_{\text{min}} \) is the minimum stomatal resistance (s m\(^{-1}\)).

Thus, the energy balance equation on the vegetation surface can be expressed as
\[
C_v \frac{\partial T_v}{\partial t} = R_{n_v} - H_v - \text{LE}_v,
\]
where \( C_v \) is the heat capacity of vegetation (J m\(^{-2}\) K\(^{-1}\)) and can be calculated as
\[
C_v = 4186 \times \text{LAI},
\]
which is equivalent to the heat capacity of 1-mm water depth per leaf area index (LAI) (Garratt 1992).

3) GROUND SUBSYSTEM

The sensible heat flux on the ground surface (W m\(^{-2}\)) is
\[
H_g = \rho_a c_p V_a(T_{gs} - T_a),
\]
where \( c_p \) is the specific heat capacity of dry air (J kg\(^{-1}\) K\(^{-1}\)) and \( K_{sv} \) is the turbulent diffusivities for temperature (Stull 1988).

The moisture flux on the ground surface (kg m\(^{-2}\) s\(^{-1}\)) is
\[
E_g = \rho_a K_{sv} V_a h u q_{\text{sat}}(T_{gs}) - qa,
\]
where \( h_u \) is the relative humidity at surface, \( K_{sv} \) is the turbulent diffusivities for water vapor (Stull 1988), and \( q_{\text{sat}}(T_{gs}) \) is the saturation specific humidity (kg kg\(^{-1}\)) when the ground surface temperature is \( T_{gs} \), calculated according to Teten’s equation:
es\(e_s(T_s) = 6.1 \times \exp\left(17.269 \times \frac{T_s - 273.16}{T_s - 35.86}\right)\) \hspace{1cm} \text{(21)}

\[q_{\text{sat}}(T_s) = 0.622 \frac{e_s(T_s)}{p - 0.378 e_s(T_s)}.\] \hspace{1cm} \text{(22)}

Thus, the surface energy balance equation is given by

\[C \frac{\partial T_g}{\partial t} = R_n - H_g - \lambda E_g.\] \hspace{1cm} \text{(23)}

3. Validation of the model and numerical tests design

a. Simulation domain

This study is focused on Suzhou City, which is located in the middle part of the delta region of the Yangtze River (see Fig. 2) that is one of the most developed and fastest-growing areas in China. Suzhou City covers 1650 km\(^2\) with a population of 2.4 million. The city endures a typical humid subtropical marine climate under the effect of the East Asia monsoon and is characterized by hot and humid summers. Suzhou City high-rise morphology is relatively high with an average building height of about 19 m. In addition, Suzhou is also an environmentally friendly city and has been named as one of the National Garden Cities of China for its relatively high level of urban greening. The main species of trees applied to Suzhou’s greening belong to broadleaf forests. The average per capita green space area of Suzhou City is 14.9 m\(^2\) \hspace{1cm} \text{(Statistics Bureau of Suzhou City 2011). However, rapid economic development and ongoing urbanization processes in this region have led to a conversion of the underlying surface from vegetated areas (trees; lawns) to artificial surfaces (roads; buildings), which could cause some deterioration of the local living environment. This study seeks to evaluate the thermal effects of greening on the urban microclimate; this may provide a scientific basis to government officials involved in urban planning, design, and implementation of greening efforts. Suzhou City is typical of East Asia metropolises for its hot and humid summers, rapid economic and urbanization development, and endeavors to introduce more greenery into urban areas.

The simulation domain includes 95 × 95 grid points, with a horizontal resolution of 1 km × 1 km, which covers four cities including Suzhou, Wuxi, Changshu, and Kunshan City. Suzhou City is located in the middle of the domain and is centered at 31.26°N, 120.63°E. The land-use types in the domain include urban, grass, forest, water, and cropland (see Fig. 3a). Figure 3b shows the distribution of vegetation coverage (VC) in the model domain, which is obtained from the Landsat-5 25 m × 25 m high-resolution satellite observations. As the model resolution is 1 km × 1 km, each model grid contains 40 × 40 \( (1 \text{ km}/25 \text{ m} = 40) \) subgrids. Thus, the vegetation coverage of each grid is defined as the proportion of tree and grass subgrids in each grid.

The mean VC in Suzhou City is 21.5%, including tree coverage of 17.9% and grass coverage of 3.6%. Most greenery is concentrated in the urban fringe area (VC \( \sim \) 30%–40%), whereas in the densely populated center area VC is lower \( (<10\%\) ). The greening schemes discussed in this study are expected to improve urban greenery of all built-up areas, not only the fringe area.

b. Synoptic conditions

In the summer of 2013, large areas of southern China suffered through a severe, sustained hot-weather event (temperatures exceeding 35°C can be defined as hot weather according to the China Meteorological Administration). The observed daily maximum temperature at Suzhou’s meteorological station was maintained at a relatively high level \( (>35\degree C) \) in most days from July to August 2013, and even exceeded 40°C for several days in a row. This kind of extreme weather will have a range of consequences for human health; for example, increased rates of heat stroke, hyperthermia, and mortality \( \text{(Stott et al. 2004; Tan et al. 2007).} \)

c. Numerical tests design

To investigate the role of urban greenery in moderating urban climate, the new version of the RBLM was employed to simulate a hot-weather episode from 5 August to 12 August 2013. During this period, the
observed daily maximum temperatures in Suzhou City were all well above 35°C. The surface observation data for 0800 LST 5 August 2013 obtained from four meteorological stations (Suzhou, Changshu, Kunshan, and Dongshan, as shown in Fig. 3a) are used to initialize the RBLM, including 2-m air temperature (°C), surface pressure (Pa), 2-m relative humidity (%), surface skin temperature (°C), and 10-m wind speed (m s⁻¹) and direction (°). In addition, vertical sounding data for initialization were used by interpolating the National Centers for Environmental Prediction–National Center for Atmospheric Research 1° × 1° reanalysis data into the RBLM grids. The land-use type used in the model is obtained from Landsat-5 satellite observations (see Fig. 3a). The vertical resolution of the model has 33 layers, which use the terrain-following sigma coordinates. There are about 15 vertical layers in the PBL; the lowest-layer depth is around 30 m, and the top layer is up to about 4500 m. The numerical integration for the simulations was started at 0800 LST 5 August 2013 and ended at 0000 LST 13 August 2013.

d. Model evaluation

To validate the performance of the new version of RBLM, the simulation results are compared with the observation data collected from four meteorological stations (the station locations are illustrated in Fig. 3a) from 0800 LST 5 August to 0000 LST 13 August 2013. Figure 4 shows the comparison between simulations and observations of four meteorological elements, including 2-m temperature, 10-m wind speed, 2-m relative humidity, and surface skin temperature at the Suzhou meteorological station. The agreement between the hourly observations and the simulation results is evaluated using mean bias (MB), normalized mean bias (NMB), root-mean-square error (RMSE), and correlation coefficient (R). Results of these statistics at the Suzhou, Changshu, Kunshan, and Dongshan sites are summarized in Table 2. All of the correlation coefficients listed here are statistically significant at the 95% confidence level. In general, air temperature (NMBs up to ±3%, RMSEs up to 1.88, and R is 0.85–0.92), relative humidity (NMBs up to −8.88%, RMSEs up to 11.70, and R is 0.80–0.87), and surface skin temperature (NMBs up to −8.62%, RMSEs up to 6.08, and R is 0.88–0.96, except for the Dongshan site) are reproduced well by the new version of the RBLM, although the surface temperature at the Dongshan site is underestimated by 25%. This is probably because the land-use type in the vicinity of the Dongshan site is pretty complex and spatially variable (as shown in Fig. 3a), thus resulting in an inaccurate representation in the model. In addition, the calculation of surface temperature is very sensitive to the land-use type that the model uses, thus leading to the underestimation. Nevertheless, the model still captures well the diurnal variation tendency of surface temperature at the Dongshan site (R = 0.9). In terms of wind speed, model calculations generally reproduce the absolute values at all stations (NMB is from −23% to 7%), although the simulated hour-to-hour variational trend is relatively poor (R is 0.17–0.51). This is probably because the surface wind is susceptible to local perturbations. The observations only
represent a very limited range around the meteorological station, whereas the simulation results stand for the average value over an area of 1 km × 1 km. This mismatch in their representative scopes may lead to the discrepancy in wind speed. Based on these comparative and statistical analyses, the results indicated that it is feasible to study the meteorological features in Suzhou area using the updated version of RBLM coupled with the forest canopy model.

e. Greenery scenarios

To evaluate the mitigation effect of different greenery schemes on hot weather episodes in the Suzhou area, a series of simulations was conducted for this study, including different percentages of vegetation coverage and different types of greenery. The setups for the cases are summarized in Table 3. The simulation Case_base describes a base case with the current urban greenery in Suzhou City in which the vegetation coverage of each grid is heterogeneously distributed based on Landsat-5 satellite observations (as shown in Fig. 3b). The simulation Case_0 is an extreme case with absolutely no vegetation in Suzhou City. Thus, the role of the current greening level in moderating local hot weather is reported by comparing the simulation results of Case_base with Case_0. Furthermore, to assess the cooling effects of different greenery scenarios, three ideal cases (Case_20_t, Case_40_t, and Case_20_g) are introduced. Simulations Case_20_t and Case_40_t are differentiated by their percentage of tree coverage in the urban area, specifically, 20% and 40%. In Case_20_g, 20% of the urban area is covered by grass. The urban greenery scenarios employed in Case_20_t, Case_40_t, and Case_20_g are all uniformly distributed with the preset vegetation coverage and greenery type. Simulation Case_noanth is designed to compare the relative contribution to the urban thermal environment between greenery and anthropogenic heat. Thus, the only difference between Case_base and Case_noanth is whether or not the impact of anthropogenic heat is taken into account in the simulation. Here, we removed the impact of anthropogenic heat by setting all four of its components (industry, residential, transportation, and metabolism) to zero. The meteorological fields used to initialize the RBLM are all the same in the six cases.

4. Results and discussion

a. Cooling effects of different urban greenery scenarios during hot summer days

Greening is beneficial in cooling the urban environment, but the cooling potential of different greening strategies also needs to be further investigated. To address this issue, the comparative results of the ideal case against the base case of simulated air temperature at 2 m
are illustrated in Fig. 5. The diurnal variation of air temperature in each case is the regional-mean value over Suzhou City (shown in Fig. 3a as the red zone within the black circle).

As shown in Fig. 5a, relative to the situation when all vegetation is removed (Case_0), the current greening situation in Suzhou City (heterogeneous distribution, as shown in Fig. 3b) contributed to a reduction of about 0.4\degree C for daily mean air temperature and a reduction of about 0.8\degree C for maximum air temperature.

For the same vegetation coverage of 20%, the comparative results of Case_20_t against the base case, as in Fig. 5b, indicate that the uniform distribution pattern of the greenery scenario is more beneficial in cooling the urban environment than is the current heterogeneous distribution pattern (high coverage in the fringe area, but low in the center). The daily mean air temperature reduction is about 0.3\degree C, while the maximum reduction is about 0.6\degree C. By further increasing the tree coverage to 40% in Case_40_t, as in Fig. 5c relative to the base case, the mean and maximum air temperature reductions can reach 1.2\degree C and 2.0\degree C, respectively.

Figures 5b and 5c clearly show that tree planting is beneficial in cooling the ambient air temperature. The cooling effect is most pronounced at noontime when the solar radiation reaches its peak value. The reduction of the ambient air temperature by trees is due to three major physical processes: 1) shading by trees reduces solar radiation reaching the ground and human bodies, 2) long waves emitted from the surface are reduced at lower surface temperatures through shading, and 3) evapotranspiration cooling occurs as a result of a combination of the effects of evaporation from wet surfaces and transpiration from plant leaves. A similar rationale is also expounded by Avissar (1996), Bowler et al. (2010), and Shashua-Bar et al. (2011). The shading effect reaches

| TABLE 2. Evaluation statistics on meteorological factors calculated by the new version of RBLM. |
|-----------------------------------------------|-----------------|----------|---------|---------|---------|
| Avg                                          | Measured        | Simulated| RMSE    | MB      | NMB (%) | R       |
| Suzhou site (31.26°N, 120.63°E)              |                 |          |         |         |         |         |
| Air temperature at 2 m (°C)                  | 34.6            | 34.9     | 1.62    | 0.32    | 0.92    | 0.88    |
| Wind speed at 10 m (m·s\(^{-1}\))           | 1.97            | 2.12     | 0.97    | 0.14    | 7.23    | 0.30    |
| Relative humidity at 2 m (%)                 | 57.88           | 54.46    | 11.26   | -3.42   | -5.90   | 0.81    |
| Surface skin temperature (°C)                | 40.7            | 39.2     | 6.08    | -1.52   | -3.72   | 0.88    |
| Changshu site (31.65°N, 120.74°E)           |                 |          |         |         |         |         |
| Air temperature at 2 m (°C)                  | 33.9            | 34.9     | 1.60    | 1.02    | 3.00    | 0.92    |
| Wind speed at 10 m (m·s\(^{-1}\))           | 1.84            | 1.68     | 0.84    | -0.16   | -9.0    | 0.51    |
| Relative humidity at 2 m (%)                 | 60.3            | 54.9     | 9.84    | -5.35   | -8.88   | 0.87    |
| Surface skin temperature (°C)                | 40.3            | 36.8     | 5.81    | -3.48   | -8.62   | 0.92    |
| Kunshan site (31.41°N, 120.95°E)            |                 |          |         |         |         |         |
| Air temperature at 2 m (°C)                  | 34.4            | 35.2     | 1.67    | 0.75    | 2.18    | 0.89    |
| Wind speed at 10 m (m·s\(^{-1}\))           | 2.21            | 1.78     | 1.19    | -0.43   | -19.28  | 0.17    |
| Relative humidity at 2 m (%)                 | 55.0            | 53.4     | 8.73    | -1.59   | -2.90   | 0.84    |
| Surface skin temperature (°C)                | 41.3            | 39.6     | 4.14    | -1.74   | -4.21   | 0.96    |
| Dongshan site (31.06°N, 120.43°E)           |                 |          |         |         |         |         |
| Air temperature at 2 m (°C)                  | 34.1            | 33.7     | 1.88    | -1.03   | -3.03   | 0.85    |
| Wind speed at 10 m (m·s\(^{-1}\))           | 2.30            | 1.77     | 1.17    | -0.53   | -23.20  | 0.26    |
| Relative humidity at 2 m (%)                 | 62.3            | 58.9     | 11.70   | -3.32   | -5.33   | 0.80    |
| Surface skin temperature (°C)                | 40.1            | 30.1     | 12.37   | -10.02  | -24.95  | 0.90    |

| TABLE 3. A summary of the study cases. |
|---------------------------------------|----------------|------------|----------|
| Vegetation coverage ratio            | Type of greenery | Consideration of anthropogenic heat (yes/no) |
| Case_base                            | Heterogeneous distribution based on Landsat-5 observations (%) | Tree and grass | Y          |
| Case_0                               | 0              | No         | Y         |
| Case_20_t                            | 20             | Tree       | Y         |
| Case_40_t                            | 40             | Tree       | Y         |
| Case_20_g                            | 20             | Grass      | Y         |
| Case_noanth                          | Same as Case_base | Same as Case_base | N         |
its maximum efficiency when synchronized with solar radiation at noontime, thus leading to a maximum air temperature reduction.

For grass surfaces (Fig. 5d) with grass coverage by 20% (Case_20_g), the daily mean air temperature reduction (about 0.2°C) is slightly less than that of tree planting with the same coverage (Case_20_t). Additionally, its diurnal variation pattern of temperature reduction is quite different from tree greening with the most notable cooling in the evening and a slight warming at noontime. This is probably because, for grass surfaces, the ground is completely exposed to the sky without radiation blockage from trees or buildings; that is, the sky-view factor is greater in Case_20_g. Consequently, in the daytime, more solar radiation can reach and heat the ground and counteract the cooling effect induced by evapotranspiration. At noontime, the increment of solar heating reaches its maximum value and exceeds the effect of evapotranspiration cooling, thus leading to a slight warming. While at night, the net longwave loss is enhanced due to the increased sky-view factor. Hence, the cooling effect during the night is more notable. The simulation results are in line with the study of Potchter et al. (2006), who conducted an observation study in Tel Aviv, Israel, and found that an urban park covered with grass can sometimes be warmer than the built-up area during the daytime and cooler at night.

To conduct a comprehensive analysis of the relative contributions of urban greenery to an urban thermal environment, an ideal case was created wherein all the anthropogenic heat generated in Suzhou City was removed. Figure 5e shows the results of the air temperature reduction caused by the removal of all the anthropogenic heat generated in Suzhou. The daily mean temperature reduction is about 0.7°C, while the maximum temperature reduction can reach 1.2°C around 1900 LST. This is probably because, in the Case_base simulations, a large amount of anthropogenic heat generated during the daytime has been stored within the urban canopy structure, and then released at night. This is also one of the reasons why the urban heat island is generally stronger at night. On the contrary, however, when all anthropogenic heat is removed in Case_noanth, the cooling effect is more noticeable in the evening. Memon et al. (2008) summarized and reviewed the methods that can be used for mitigation of UHIs and suggested reduced anthropogenic heat release and increased urban greenery as two possible measures. In comparison with the latter, reducing anthropogenic heat release is more difficult and inefficient in practical applications because nearly all...
human activities generate heat. In this study, a comparison between Figs. 5c and 5e indicates that with tree coverage of 40%, the cooling effect on the urban thermal environment will exceed that of removing all anthropogenic heat in terms of the daily mean temperature.

Several conclusions can be made by the comparative results. Vegetation can substantially affect the temperature of urban areas. The cooling effect is higher with increased vegetation coverage. Tree planting is more effective than are grass surfaces in urban cooling, especially with regard to daily maximum air temperatures at noontime. These conclusions are quite in line with other research, such as that of Sebba et al. (1984), Potchter et al. (2006), and Ng et al. (2012).

Figure 6 shows the simulated diurnal variations of near-surface temperature over urban areas (the red shadowed area circled in Fig. 3a) in different cases. The horizontal line indicates the threshold value (35°C) for the definition of hot weather. The total and daily mean hot-weather hours (i.e., hours during which the air temperature exceeds 35°C) from 5 to 12 August 2013 are summarized in Table 4. The results indicate that the simulation of the base case is consistent with the observations, which in turn verifies the satisfactory performance of the RBLM.

The current greening situation in Suzhou City is beneficial for cooling the urban environment, which leads to a reduction of 1 h of the daily mean hot-weather hours (see Table 4, the comparison between Case_base and Case_0). As illustrated in Fig. 6, the comparison between Case_base and Case_0 shows a varying degree of temperature reductions throughout the day. In addition, the cooling effect is more significant from 1200 to 1400 LST, as previously stated.

Considering only tree greening with coverage of 20% (Case_20_t), the air temperature is further lowered but only to a limited extent. When the tree coverage was increased to 40% (Case_40_t), the cooling effect over urban areas became more pronounced. The air temperature overall declines throughout the day, while the daily mean hot weather hours sharply decreased by about 3 h (see Table 4).

For grass surfaces only with coverage of 20%, there seems to be little difference between Case_20_g and Case_20_t in terms of hot weather hours (as presented in Table 4). However, as shown in Fig. 6, the noontime air temperature in Case_20_t is apparently lower than that in Case_base, indicating that tree planting is fairly effective at lowering the air temperature at noontime (i.e., daily maximum temperature). Nonetheless, the hot weather hours show little variation, because the ambient temperature at noontime is well above 35°C during the study period.

The results presented in this section are consistent with those of Moriyama et al. (2009). According to their study, a greenery coverage rate of 30% was found to reduce the urban air temperature by 1°C. They also suggested that for the central district of Osaka, Japan, the greenery ratio should be more than 30%.

Figure 7 shows the spatial distribution of daily mean air temperature at 2 m averaged over the period of 5–12 August 2013 in different cases. The Case_base simulation (Fig. 7a) indicates that the daily mean air temperature over urban areas is higher than those in the surrounding rural areas in the model domain by up to 2°C; that is, obvious UHI phenomena existed in the areas around Suzhou. When the vegetation is all removed (Case_0), the UHI effect intensifies, along with an obvious expansion of its size (Fig. 7b). Relative to Case_base, Fig. 7c shows an overall reduction tendency for daily mean air temperature in urban areas, indicating that tree coverage of 20% (Case_20_t) is more beneficial in mitigating the UHI effect than the current greening situation (Case_base, heterogeneous distribution as in Fig. 3b) during hot summer days. By increasing the tree coverage to 40% in Case_40_t, there

![Table 4. Total and daily mean hot-weather hours (i.e., hours during which the air temperature > 35°C), calculated from 5 to 12 Aug 2013.](http://journals.ametsoc.org/doi/pdf/10.1175/JAMC-D-14-0057.1)
is no visible difference in daily mean air temperature between urban and rural areas. Therefore, a greening strategy of 40% tree coverage could substantially improve the thermal environment in a city. In terms of grass surfacing, as in Fig. 7c, the cooling effect is less effective than tree planting.

The impact of different urban greenery scenarios on daytime maximum temperatures over urban areas is
similar to those of daily mean air temperatures, as mentioned above. For nighttime minimum temperature, neither tree planting nor grass surfaces exerts a noticeable influence; a “cold island” phenomenon emerges in urban areas (figures not shown) only when the tree coverage reaches 40%.

b. Impacts of different greenery scenarios on the urban heat island intensity

The simulation results of daily mean urban heat island intensity (UHII) averaged from 5 to 12 August 2013 during different cases are presented in Table 5. UHII represents the simulated near-surface temperature difference between urban and rural average values. During the simulation period, the daily mean UHII in Suzhou City is about 1.9°C, as simulated by the base case. For comparison, the Case_0 result indicates that within Suzhou City, the current greenery situation can yield a decrease in the daily mean UHII of about 0.3°C. Under the same vegetation coverage pattern (20%), tree planting is more beneficial than grass surfaces with a reduction in the daily mean UHII of 0.4°C (Case_base minus Case_20_t) for trees and 0.2°C (Case_base minus Case_20_g) for grass, respectively. When increasing the tree coverage to 40% in Case_40_t, the UHI effect in Suzhou can be substantially moderated by reducing the daily mean UHII to 1°C.

The cooling effect of a green area increases with its size (Bowler et al. 2010). However, from an urban planning perspective, implementation of vegetation to 50% coverage within the high-density urban context is either difficult or impractical (Ng et al. 2012). Therefore, based on the simulation results of this study, tree coverage of around 40% may be a relatively optimized urban greenery scheme.

c. Impacts of different greenery scenarios on surface energy balance over urban areas

To further explore the role of tree planting on modifying the surface energy balance over urban areas, a clear day (8 August 2013) was selected for investigation. Figure 8 shows the simulated diurnal variations of each component of the surface energy balance in different cases. The shading effect of trees can directly affect the amount of solar radiation that reaches the ground surface, so the surface net radiation is reduced by increasing tree coverage. As presented in Fig. 8, when the tree coverage changes from 0%–20% and then to 40%, the average surface net radiation fluxes at noon (1200 LST) are 591, 512, and 421 W m⁻², respectively.

In addition to the shading effect, tree planting can also alter the surface energy balance by providing sources of moisture for evapotranspiration. More absorbed radiation can be dissipated into latent heat rather than sensible heat when increasing tree coverage. For example, the average surface sensible (latent) heat flux is 281 (32) W m⁻² in Case_0, and the Bowen ratio is 8.78 at noon (1200 LST). In Case_20_t, the sensible (latent) heat flux is 198 (166) W m⁻², while the Bowen ratio is sharply reduced to 1.20. Further in Case_40_t, the sensible (latent) heat flux is 113 (264) W m⁻², and the Bowen ratio is only 0.43. Therefore, the urban temperature can be reduced by tree coverage.

5. Conclusions

A forest canopy model was coupled into the RBLM to fully explore the impacts of tree planting and grass surfaces on an urban thermal environment using high-resolution (25 m × 25 m) land cover data obtained from Landsat-5 satellite observations. The performance of the new version of RBLM was evaluated using meteorological station observations within the model domain. The results suggest that the model reproduces well the meteorological features in the Suzhou area.

Further, the impacts of different greenery scenarios on the thermal environment of Suzhou City during the hot weather episode from 5 to 12 August 2013 were analyzed. The current greenery situation within Suzhou City has already contributed to a reduction in the ambient air temperature. This cooling effect will be more pronounced if the vegetation is uniformly distributed throughout Suzhou City, rather than concentrated in the urban fringe, as it is now. According to different greenery scenarios, both tree planting and grass surfaces are beneficial in cooling the ambient air temperature. Tree planting is in general more beneficial than grass surfaces with the same coverage. Trees can reduce the ambient air temperature through three major physical processes, including shading effects, surface longwave radiation reduction, and evapotranspiration cooling. The cooling effects of trees are more notable at noontime and can remarkably reduce the daily maximum air temperature in urban areas. The cooling effect of urban greenery increases with increasing coverage. With regards to a surface energy balance, by increasing

<table>
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tree coverage from 0 to 20%, and then to 40%, the average surface net radiation fluxes at noon (1200 LST) were 591, 512, and 421 W m$^{-2}$, respectively. Correspondingly, the Bowen ratios were reduced from 8.78 to 1.20, and 0.43 as a result of the redistribution of solar energy absorbed at the ground into latent heat. However, too much vegetation coverage within a high-density urban context is either difficult to achieve or impractical. Thus, based on the simulation results of this study, tree coverage of around 40% may be a relatively optimized urban greenery scheme.

Although the impacts of different greenery scenarios on the thermal environment of Suzhou City were investigated with the new version of RBLM, there still exist limitations in this study. Owing to the lack of in situ measured parameter values associated with soil and vegetation, the accuracy of the modeling may to some extent be biased. Thus, further studies should pay more attention to obtaining parameter values that are more specific to the research domain. Although limitations exist, the conclusion of this study can help us better understand the role of vegetation in moderating the urban microclimate and provide a scientific basis to the decision makers dealing with the urban planning, design, and implementation of greening strategies.

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