Urban Forestry & Urban Greening 26 (2017) 18–24

Contents lists available at ScienceDirect

Urban Forestry & Urban Greening

journal homepage: www.elsevier.com/locate/ufug

Original article

Radiative shading effect of urban trees on cooling the regional built environment

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ARTICLE INFO

Keywords:
Built environment
Radiative shading
Regional climate
Urban mitigation strategies
WRF model

ABSTRACT

Land use and land cover changes due to urbanization have led to significant modifications in the built environment at both local and regional scales, making adaptation/mitigation strategies imperative for the sustainable development of cities. While urban trees offer great potential for heat mitigation and enhanced environmental quality, most of the existing urban land surface models do not contain adequate representations of trees, particularly the radiative heat exchange in the canyons. In this study, we incorporated the radiative shading effect of urban trees into the state-of-the-art version of the coupled Weather Research and Forecasting-Urban Canopy Model modeling system. This modeling framework, albeit at its infancy, is applied to the Phoenix Metropolitan area to study the regional cooling effect of trees in an arid environment. Simulation results demonstrated the capacity of urban trees in reducing urban surface and air temperature by about 2 ~ 9 °C and 1 ~ 5 °C respectively and increasing relative humidity by 10 ~ 20% during a mean diurnal cycle; the effect is more prominent during nighttime.

1. Introduction

Global population is undergoing rapid urbanization; more than half (54%) of the world's population is living in cities, and the proportion is projected to increase to 66% by 2060 (United Nations, 2014). The conversion from natural landscapes to the built environment, concomitant with the rapid urbanization, induces modifications of surface energy and hydrologic balance, leading to changes of urban microclimate (Arnfield, 2003). Specifically, the change in amount of radiative energy absorption and its repartitioning into latent and sensible heat due to landscape modification modulate heat and moisture cycles at the surface as well as in near-surface air (Oke, 1987). The local signals of urban land surface changes then penetrate into the overlying atmospheric boundary layer, participate into the synoptic circulations, and thus manifest in the regional hydroclimate, via a cascade of land-atmosphere interactions (Song and Wang, 2015a). These urbanization-induced changes challenge both environmental (regional urban climate change, air quality degradation, urban heat island effect, etc.) and energy sustainability, thus accentuating the importance of adaptation/mitigation strategies in the cities (Oke, 1982; Song and Wang, 2015b; 2016). During past decades, various mitigation strategies have been proposed and implemented to alleviate excessive urban heat, including urban trees (Akbari et al., 2001; Roy et al., 2012), reflective pavements (Yang et al., 2015b), and green roof systems (Yang et al., 2016).

Urban trees present a feasible form of urban green infrastructures for heat mitigation. The shading effect of urban trees reduces the net energy absorption thus modifying the urban energy balance (Roy et al., 2012) and cooling the urban canopy and boundary layers by reducing the sensible heat (Armson et al., 2012; Rahman et al., 2015). The participatory role of urban trees with its shading effects and evapotranspiration in urban land-atmosphere interactions also assists in improving the building energy efficiency by declining cooling demand (Akbari et al., 2001). The houses with shade trees have shown decrease in peak cooling demand of over 30% in previous studies (Akbari et al., 1997). Similarly, shade trees also contribute to human thermal comfort by reducing surface and air temperatures and reducing direct and diffusive shortwave (solar) radiation from reaching canyon facets (Hedquist and Brazel, 2014; de Abreu-Harbicha et al., 2015).

The effects of shading and evapotranspiration of trees on the built environment have triggered various research efforts to incorporate trees in urban modeling systems. Lee and Park (2008) included trees in the vegetated urban canopy model (VUCM) by including the hydrological processes of trees via evapotranspiration (ET), but without taking into account the effect of radiative shading. Krayenhoff et al. (2014) included the radiative effects of tall trees in multi-layer urban canopy model (UCM) based on Monte Carlo ray-tracing method. Wang (2014) integrated urban trees into a single-layer UCM, enabling heat exchange between trees and urban facets via modifications of the radiative view

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http://dx.doi.org/10.1016/j.ufug.2017.05.008
Received 9 September 2016; Received in revised form 5 May 2017; Accepted 12 May 2017
Available online 31 May 2017

factors. This modified view factors was later adopted by (Ryu et al., 2016), together with other biophysical processes of urban trees such as ET. Song and Wang (2015a, 2015b) integrated urban trees into a single column atmospheric model, and used it to investigate the impact of urban trees on urban boundary-layer dynamics. These studies using offline (stand-alone) UCMs have shown that the inclusion of trees has significant impacts on predicting the overall cooling effect by urban green infrastructures for the local environment at the suburban (neighborhood to city) scales (Song and Wang, 2016; Wang et al., 2016). However, these studies are offline in the sense that the urban land surface processes with trees included are not fully interactive with the driving environmental forcings, resulting in potential errors in quantifying the actual effect of trees in an integrated land-atmosphere system.

For online platforms with fully coupled land-atmospheric dynamic modules, such as the Weather Research and Forecasting (WRF) model, the incorporation of the shading effect of urban trees not only allows an enhanced accuracy in predicting regional climate, but also has significant implications to sustainable urban planning in, e.g. building energy efficiency (Akbari et al., 1997, 2001). Among the developed urban modeling systems, the single-layer UCM (Kusaka et al., 2001; Masson, 2000) integrated into the WRF platform (Chen et al., 2011) has undergone continuous improvements and been widely used (Wang et al., 2013; Yang et al., 2015a) for accounting the land-atmosphere feedback and predicting urban hydroclimate. Nevertheless, modeling of water and energy budgets related to urban trees remains largely inadequate and presents as an open challenge hitherto in WRF-UCMs (Krayenhoff et al., 2014, 2015; Ryu et al., 2016). Numerical difficulty still persists in resolving the participatory role of trees in the exchange of radiative energy in built terrains (viz. shading by blockage of direct solar radiation, and trapping of terrestrial radiation) (Krayenhoff et al., 2014; Wang, 2014).

The purpose of the present study is to incorporate urban trees to be participatory into the fully coupled WRF-UCM system, by including the shading/trapping effect (Fig. 1) in radiative heat exchange in street canyons. This study applied the Monte Carlo method for radiative exchange in 2D street canyons, integrating urban trees and their shading effect derived by a previous study (Wang, 2014). With the integrated model, fully coupled regional scale simulations were carried out for the Phoenix Metropolitan area.

2. Methodology

2.1. Representing urban trees in WRF

The presence of trees in a canyon interrupts the radiative rays transmitted between the canyon facets and modifies the view factors between them. A stochastic ray-tracing method based on the Monte Carlo algorithm was adopted for capturing the radiative exchange processes inside the street canyon with trees (Wang, 2014). This method has been widely used in previous studies with urban trees (Krayenhoff et al., 2014; Ryu et al., 2016; Wang, 2014) because of its simplicity, flexibility, and robustness of implementation.

For the application of the Monte Carlo ray-tracing method and its subsequent incorporation into WRF-UCM, following assumptions were made: (a) Two symmetric rows of trees are present in the street canyon, with the cylindrical crown size of radius R_t (see Fig. 1); (b) The ray blocking effect of tree trunks is negligible considering their small size relative to the tree crown; (c) Radiative thermal energy is diffusive and decomposed of bundles of rays, each with separately generated and traced trajectory; and the emitting direction for each ray is generated by random numbers; (d) All facets (roads, walls, and trees) involved in the radiative exchange are Lambertian and gray. In the street canyon, vertical perpendicular distance from the tree crown center to the ground (h_t) and horizontal perpendicular distance from the tree crown center to the nearest wall (d_t) are used to determine the spatial location of the trees inside the street canyon, as shown in Fig. 1.

Radiative ray emitted from a canyon facet is traced by the direction of the ray from a generic i-th surface, which is determined by the azimuth angle η_i and the polar angle θ_i:

$$\eta_i = \arcsin(\sqrt{R_\eta}) \tag{1}$$

$$\theta_i = 2\pi R_\theta \tag{2}$$

where $R\eta$ and $R\theta$ are independent random numbers. The Monte Carlo algorithm is applied to trace along the randomly generated direction for the emitted ray. If this emitted ray is absorbed by a surface j, it is taken into account of the view factor F_{ij}. Indices i and j range from 1 to 6, representing the six canyon facets presented in the radiative exchange processes, i.e. the sky, the ground, two facing walls, and two symmetric tree crowns. The shading effect of trees is then determined by the modified sky view factors with the presence of trees in the canyon.

For more realistic representation of urban trees in the study area, the Survey 200 dataset of urban trees retrieved from the Central Arizona-Phoenix Long Term Ecological Research (CAP-LTER) project was analyzed to obtain information of tree in Phoenix region. Height and crown radius required for the parameterization of trees in the urban canopy model was acquired from the tree dataset for all urban categories (commercial, high-density residential, and low-density residential) presented in WRF, with different canyon aspect ratios (building height/road width). The obtained information was then applied for estimating the sky view factors using aforementioned Monte Carlo algorithm, as a function of urban geometry and tree sizes and locations.

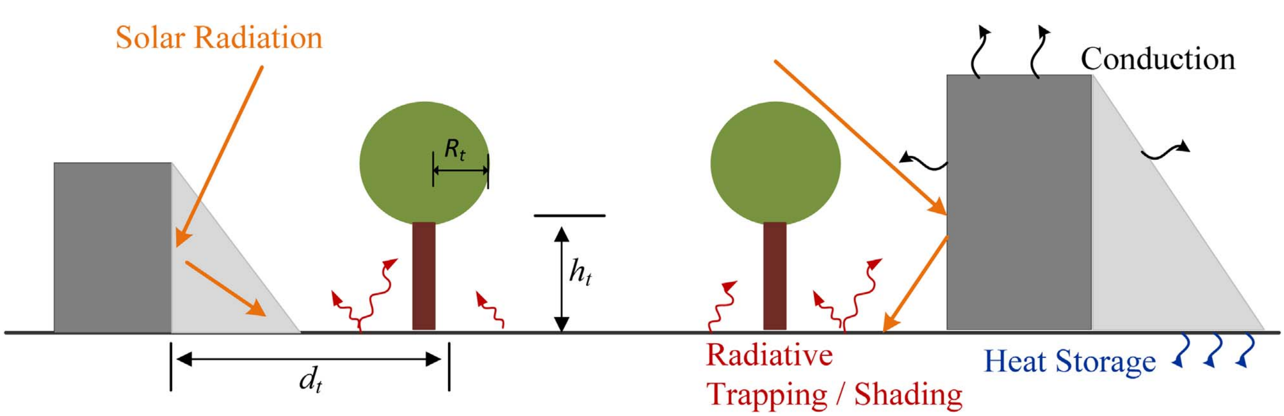

Fig. 1. Schematic diagram of thermal energy exchange in urban canopy with radiative shading by trees. R, h, and d denote the tree crown radius, height, and distance from wall, respectively, with subscript 't' standing for trees.