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Effect of pavement thermal properties on mitigating urban heat islands: A multi-scale modeling case study in Phoenix

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ABSTRACT

Engineered pavements cover a large fraction of cities and offer significant potential for urban heat island mitigation. Though rapidly increasing research efforts have been devoted to the study of pavement materials, thermal interactions between buildings and the ambient environment are mostly neglected. In this study, numerical models featuring a realistic representation of building-environment thermal interactions, were applied to quantify the effect of pavements on the urban thermal environment at multiple scales. It was found that performance of pavements inside the canyon was largely determined by the canyon geometry. In a high-density residential area, modifying pavements had insignificant effect on the wall temperature and building energy consumption. At a regional scale, various pavement types were also found to have a limited cooling effect on land surface temperature and 2-m air temperature for metropolitan Phoenix. In the context of global climate change, the effect of pavement was evaluated in terms of the equivalent CO_2 emission. Equivalent CO_2 emission offset by reflective pavements in urban canyons was only about 13.9–46.6% of that without building canopies, depending on the canyon geometry. This study revealed the importance of building-environment thermal interactions in determining thermal conditions inside the urban canopy.

1. Introduction

Urban heat island (UHI), a presence of higher temperatures in an urban area as compared to its rural surroundings, has been considered as one of the major problems in the 21st century [1]. Using satellite-measured surface temperatures, a higher UHI intensity was usually found in summer than that in winter [2]. The adverse effects induced by UHI include but are not limited to, elevated temperatures [3], increased energy consumption [4], air pollution [5], heat-related mortality [6], and disruption to ecosystems [7]. Under the challenge of future climate change, UHI makes cities become unprecedentedly vulnerable to environmental problems that research efforts have been devoted to developing and testing adaptation/mitigation strategies during the past decades [8,9]. Recognized strategies include reflective roofs [10,11], green roofs [12,13], urban vegetation and shading [14–16], heat sinks [17], and cool pavements [18]. Due to the space restrictions in the urban environment, roof material has been extensively studied while pavement material on the ground level has gained limited attention.

Paved surfaces, including roads, parking areas and sidewalks, cover a significant percentage of urban surfaces. A previous study reported that the percentage of paved surfaces ranged from 30 to 39% as seen from above the urban canopy, and from 36 to 45% as seen from under the canopy for a variety of metropolitan areas [19]. With such a significant percentage, modification of pavement materials provides a large potential for mitigating urban heat islands. Though a couple of studies have illustrated the capacity of pavements in reducing UHI and building energy consumption, thermal interactions between buildings and the surrounding microclimate in urban canopies are largely neglected [20]. Different from roof materials, pavement are located inside the urban canyon where buildings substantially alter the heat transport via shading and reflecting radiations. With a three-dimensional building-to-canopy model, Yaghoobian and Kleissl [21] showed that the reflected solar radiation from the reflective pavement can increase annual cooling loads of nearby office buildings by up to 11% in Phoenix. Li [22] conducted an experimental study in Davis, California and observed that around noon on sunny summer days, the

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temperature of building walls was 2–5 °C hotter over concrete pavements than over asphalt pavements. Incorporation of the environmental complexity of built terrains is therefore of critical importance in order to provide useful guidance to energy-efficient designs of buildings and paved surfaces, leading to sustainable city planning. In addition, most existing studies have focused on retrofitting pavements with high albedo or reflective construction materials, thus other pavement materials, such as ones with different thermal capacity and conductivity, have been less studied as strategies for UHI mitigation.

Existing studies on the impact of pavements on the urban thermal environment focused on the building-resolving scales and explored offline models where meteorological forcing is provided as boundary conditions [20]. Geographical complexities at city and regional scales, such as spatial heterogeneity, variability in building geometry and density, and local air circulation, are not properly represented. In addition, land-atmosphere interactions are largely neglected in offline models, i.e., meteorological conditions do not respond to changes in building physics. Due to theses limitations, upscaling the results of offline studies for guidance at city and regional scales becomes challenging [23]. Accurate quantification of the effect of pavements on the urban thermal environment necessarily requires studies in a fully-interacting environment, i.e., a coupled atmosphere-urban modeling system.

In this study, the main objective was to evaluate the effect of pavement thermal properties on the urban thermal environment at multiple scales. Towards this end, numerical models were applied with building-environment thermal interactions to: 1) analyze the sensitivity of pavement surface temperature to canyon geometry, 2) identify the impact of pavement thermal properties on the surface temperature, building energy consumption, and outdoor human thermal comfort at a neighborhood scale, and 3) assess the effect of pavement thermal properties in mitigating UHI at a regional scale. The metropolitan Phoenix in Arizona was selected as the testbed because of the rapid urbanization in the past decades which has created a significant UHI in this region. The equivalent CO_2 emission offset by reflective pavement due to modified radiative forcing at the global scale was also estimated and discussed.

2. Numerical tools and study area

This section describes the numerical tools used to investigate impacts of pavements in the built environment in this study. An offline (stand-alone) urban canopy model was adopted for studying the impact at the neighborhood scale. The offline model is suitable for long-term simulations at the neighborhood scale due to its high computational efficiency. However, land-atmosphere interactions are largely neglected in the offline model. At the city and regional scales, an online (coupled) Weather Research and Forecasting (WRF)-Urban modeling system was used to account for the land-atmosphere interactions and surface heterogeneity. Nevertheless, the requirement of high-performance computational resources imposes constraints on spatial resolution and simulation time of online models.

2.1. Urban canopy model

To accurately quantify the impact of pavements in the built environment, a numerical model that captures coupled urban energy and water budgets is needed. Here a state-of-the-art urban canopy model (UCM) [24,25] was used. The UCM represents building arrays as a two-dimensional street canyon, as illustrated in Fig. 1(a). The model features a realistic representation of hydrological processes over natural and engineered surfaces, sub-facet heterogeneity, building-environment thermal interaction in the canyon, and analytical solutions to heat transfer in building envelopes. Model performances over various pavement surfaces in the urban area have been validated by in-situ measurements under different climate conditions [25,26]. Detailed computational processes of the model can be found in the original paper and thus are not duplicated here.

2.2. WRF-urban modeling system

During the past decades, a growing concern on urban heat island has led to development of numerous mesoscale atmosphere-urban modeling systems [27–29]. Among the developed systems, one powerful tool is the WRF-Urban modeling system, which has been widely utilized and examined for major metropolitan regions around the world [30–32]. In this study the developed urban canopy model was implemented into the WRF model version 3.4.1 and the new model was employed to access the impact of pavements at the regional scale. Initial meteorological conditions for the WRF simulations were obtained from the National Centers for Environmental Prediction Final Operational Global Analysis data, which were available on a 1° × 1° resolution with a 6-h temporal frequency (details can be found on http://rda.ucar.edu/datasets/ds083.2/). Land use information was acquired from the National Land Cover Database (NLCD) 2006 [33].

2.3. Study area

For the urban canopy model, meteorological measurements in the atmospheric boundary layer are required as model inputs. Observations obtained from the eddy-covariance flux tower deployed at Maryvale, west Phoenix (see Fig. 1(b)) were used to drive offline simulations. The experimental site is a high-density residential area with single-family houses with a mean lot size of about 700 m^2 [34]. Generally, the daily mean incoming shortwave radiation is greater than 600 W m^{-2} and the daily mean air temperature at 22 m is higher than 30 °C in summer. The monsoon season starts June 29 and ends September 30. The wind speed in the study area is about 3 m s^{-1} in summer, with a prevailing wind direction towards the west [34].

3. Effect of canyon geometry

Urban geometry plays a crucial role in determining the magnitude of shading and trapping effects that its impact on pavement surface temperature needs to be addressed [35]. In this section the sensitivity of pavement surface temperature to canyon geometry was analyzed with the urban canopy model. Capability of the model in reproducing energy and water budgets of the study residential area at the annual scale (year 2012) was verified in a previous study [36]. The calibrated parameters were summarized in Table 1 and were used for subsequent offline numerical simulations. As reflective pavement has gained increasing popularity recently, it was used as an example to illustrate the effect of canyon geometry. Focusing on the time when the urban thermal environment is extremely aggravated, numerical simulations were carried out for a pre-monsoon summer period, 12–17 June 2012, when high temperatures were observed under clear sky conditions. Pavements were modeled with an albedo (the ratio of reflected radiation from the surface to incident radiation upon it) of 0.1, 0.3, 0.5 and 0.7, while other thermal properties remained the same as shown in Table 1. The first set of simulation modeled a pavement surface without canopy (e.g., open ground space, parking lot), while the second set simulated a pavement surface in the canyon of a typical high-density residential area.

Averaged diurnal profiles of pavement surface temperature are