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The impact of building density and building height heterogeneity on average urban albedo and street surface temperature

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ABSTRACT

A three-dimensional numerical model (the Model for Urban Surface Temperature – MUST) was used to investigate the impact of urban geometry on average urban albedo and street surface temperature. Satisfactory performance of the model in predicting urban albedo was confirmed. The calculated results for different canyon geometries show that: 1) the medium density urban condition (plan area index $\lambda_p = 0.44$) absorbs the most solar radiation and thus has the lowest urban average albedo; 2) the average urban albedo decreases with increasing building height; and 3) in general, more solar radiation is absorbed as building height differences become much greater. Therefore, the average urban albedo is the least for a medium density city having high-rise buildings with greater building height differences. The relationship between sky-view factor and street surface temperature was also examined. The model predicted a cooler urban street surface temperature with a smaller daily amplitude and earlier occurrence of the daily maximum temperature for a high-rise high density city when compared to a low-rise low density city. Horizontal surfaces in an urban area play an important role in determining the average urban albedo. A linear relationship was found between the average sky-view factor of horizontal surfaces and the average urban albedo.

1. Introduction

Oke [28] listed seven commonly hypothesised causes of the urban heat island effect, three of which, i.e. increased absorption of shortwave radiation; decreased long-wave radiation loss; decreased total turbulent heat transport, are related to urban street geometry changes resulting from the urbanisation process. On one hand, buildings act as blocks to alter wind profile and reduce wind speed in the canopy, which may contribute to sensible heat flux reduction from building surfaces [8,16]. On the other hand, the urban geometry may significantly influence the thermal environment of the urban area by providing solar shading for pedestrians, while at the same time becoming a heat trap due to radiation trapping between the urban surfaces [36] and reduced loss of longwave radiation to the sky [3,29].

The ability of urban canyons to absorb solar radiation, also called effective albedo or urban albedo, is one of the parameters contributing to the heat island phenomenon. It depends on both surface albedo, which is the reflecting power of a surface in the shortwave region of the electromagnetic spectrum, and urban geometry, which intensifies radiation absorption by multiple reflection between building surfaces [28]. Aida [1] was the first to examine the influence of surface irregularity of the urban canyon on effective albedo by experimental methods. In order to simplify and physically model the urban structure, Aida used cubic concrete blocks to represent urban canyons. A similar experiment was conducted by Kanda [19]; who also developed a numerical model for regular building arrays. Recently, Sugawara [35] conducted an airborne observation in real cities, and found that the albedo has negative correlation with the plan roof ratio and the aspect ratio of street canyons. A modelling study is an efficient alternative for understanding the parameters of effective albedo. Aida [2] developed a numerical two dimensional urban block canyon, based on Monte Carlo methods, from which the urban albedo changes due to the urban canyon geometric structure can be estimated. Kondo [21] utilised the Monte Carlo photon tracking method in a three-dimensional model to investigate the influence of urban canopy configuration on urban albedo. Another three-dimensional model, the Albedo Calculation Model, was developed by Chimklai [9]. It is based on the Vector Tracking Simulation method, which is similar

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to Monte Carlo simulation and aims to incorporate a mesoscale model. However, the relationship between the urban albedo and geometric factors is still not fully understood. This is because existing studies either aim to incorporate a mesoscale model, or because they are concerned with the many factors influencing urban albedo, but the analysis of the influence of urban geometry is not thorough. Groleau [15] applied the SOLENE Model to explain the urban morphology–albedo relationship by introducing a façade area density index. However, their conclusions may be limited to uniform building heights.

The impact of urban geometry on radiation with respect to surface energy balance is a significant cause of surface temperature differences between urban surfaces. Many previous studies have investigated the relationship between urban geometry (expressed by either the sky-view factor or the building height to street width ratio H/W) and street temperature as determined by either measurement or numerical modelling. For field observations, there are many ways to measure the surface temperature, e.g., air-borne infrared thermographs [5,20,27], automobile traverses [11,38] and in-situ measurements [6,7,17,27,31,33]. For sky-view factor measurement, fish-eye lens photography is typically used [5,7,11]. The results from different studies are somewhat contradictory because the urban canyon sky-view factor can have different effects on the street surface temperature. The correlation can be positive [6,7,31], negative [10] or neutral [25]. Similar varied findings are also presented by Upmanis and Unger [38,37]. The former study points out that the relationship changes according to the season, day and location, the characteristics of which may contribute to confusing results. The inconsistencies are understandable since physical experiments in nature are limited both in time and space, and easily influenced by the environment, which may obscure the general temperature variation trend. Therefore, numerical simulations may be a more effective method to understand the complicated causal mechanisms. A simple way to numerically assess the effect of urban geometry on street surface temperature is to conduct the simulation on a calm and cloudless night, in the absence of the solar shading effect and turbulent heat flux [3,18,29]. The results show that the street geometry alone has a significant effect on cooling rates, since the net loss of longwave radiation declines with the reduction of the sky-view factor (increase of the H/W ratio). Recent research has begun to incorporate complicated daytime shadow distribution into the urban surface energy balance models by applying either a ray tracing method [4,22] or other theoretical schemes [19,23,26,32]. However, these studies are only applicable for configurations with constant building heights. Also, although they confirm that urban morphology has an influence on the urban surface energy balance, the relationship between street surface temperature and geometric factors is still not very clear.

The purpose of this study is to apply a three-dimensional urban surface energy balance model to estimate the importance of urban geometry on urban albedo and street surface temperature, with a focus on the impact of building density and building height heterogeneity. The model takes into account multiple reflection between urban surfaces and can be used for a realistically complex city configuration. We hope this work may suggest ways urban planners might take advantage of urban morphology in designing comfortable urban thermal environments.

2. Model description

2.1. Brief description of the three-dimensional Model for Urban Surface Temperature (MUST)

In this paper, a three-dimensional numerical model, the Model for Urban Surface Temperature (MUST), is used. MUST aims to predict a detailed urban surface temperature distribution for any given day or location. Compared to other works related to prediction of temporal distributions of urban surface temperature [4,19,22], MUST has the advantage of applicability to complex urban geometry, i.e. different building heights. In MUST, the modelled area is divided into small, three-dimensional cells. Cells may contain one (e.g. in the centre of a wall), two (e.g. at the corner of two building walls) or as many as three (e.g. at the corner of two building walls and the roof) effective calculation surfaces with five possible directions. Three thermal heat transfer mechanisms (radiation, conduction and convection) are considered for each defined cell surface by assuming a uniform temperature profile. In this paper, we use the radiation sub-model of MUST to estimate solar radiation distribution and absorption by means of multiple reflection, and urban albedo will be derived accordingly. A brief description of the model is given below. For further details please refer to the work of Yang [39]. The dimension parameters which define urban geometry are shown in Fig. 1.

Since the surfaces we consider here are Lambertian, multiple reflection is calculated by Gebhart's absorption factor after defining the shape factors using the discrete transfer method [24,34]. Gebhart's absorption factor gives the percentage of energy emitted by a surface that is absorbed by another surface, after reaching the absorbing surface by all possible paths [13], and which is calculated as

$$G_{ij}^{\lambda} = F_{ij}\zeta_j^{\lambda} + \sum_{k=1}^{N} G_{kj}^{\lambda}\rho_k^{\lambda}F_{ik}, \tag{1}$$

where the surface element number $i = 1$ to N and $j = 1$ to N. For both longwave and shortwave radiation, Gebhart's absorption factor G_{ij} is different due to different absorptivity ζ and reflectivity ρ. F_{ij} represents the shape factor.

Ray tracing within the discrete transfer method is also used to determine the sunlit-shaded distributions. For each surface element, we specify the ray direction as directly opposite to the incidence of the sun. Along the ray path from a given surface, if the ray impinges on any other element, incident solar radiation cannot reach the given surface, and the surface is considered sun-shaded. In other words if the downwelling shortwave flux is non-zero at a surface, it is considered sunlit. After obtaining the radiation heat flux of each surface element, the aerodynamic formulation method is applied for estimation of the convective heat transfer coefficient, and a one-dimensional heat conduction model is used to calculate heat conduction through the ground and building envelopes. The shape factor, conduction sub-model, and the full model have been validated with existing field measurements. MUST performs well in terms of predicting surface temperature and heat fluxes [39].

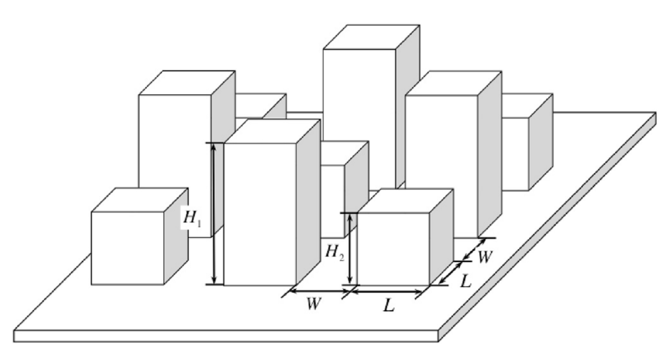

Fig. 1. Definition of the urban geometry parameters.