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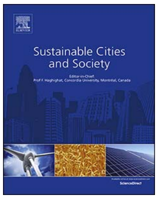

Characterization of different heat mitigation strategies in landscape to fight against heat island and improve thermal comfort in hot–humid climate (Part I): Measurement and modelling

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ABSTRACT

This study aims to consolidate and characterize the cooling potentials of heat mitigation strategies (HMSs) in landscape from both combating urban heat island (UHI) and alleviating human heat stress. This is Part I of the study, which focuses on measurement and modelling of all the possible HMSs (vegetation, albedo and water body) in landscape. The field measurement included ground level greening, different albedo pavements and water pools, which can be categorized into green, grey and blue areas. Through the microclimate simulation tool ENVI-met V4, a landscape model was developed and its performance was assessed. It was found that the variations of air temperature and mean radiant temperature within a campus landscape would be large, up to 4.5 and 32 °C respectively. The green and blue areas showed certain heat mitigation potential, but the grey areas had the possibility to generate uncomfortable thermal environment. The close relationship between microclimate and different HMSs in landscape was identified. The landscape model was capable of reproducing the main features of temporal and spatial distributions of intra-urban microclimate. Hence, the validated settings of such landscape model would be passed on for prediction of mitigation potentials of different HMSs in Part II of this study.

1. Introduction

Urban heat island (UHI) phenomenon has a clear impact on local climate, which results in higher air temperatures in dense urban areas compared to their rural surroundings. Daily mean UHI would typically range from 2 to 5 °C (Santamouris, 2007). In Hong Kong, some urban areas are experiencing an UHI of 5 °C (Ng, 2009). Severe urban living environment demonstrates strong demand to fight against UHI and improve human thermal comfort by appropriate heat mitigation strategy (HMS). Via the interplay of design creativity and scientific knowledge on the natural elements, landscape approach as a soft technology has been received growing research interest (Khalizah, Hanita, & Idilfitri, 2012; Shahidan, Jones, Gwilliam, & Salleh, 2012). In the landscape scale, three heat mitigation strategies (HMSs) have been commonly acknowledged as useful measures (Gago, Roldan, Pacheco-Torres, & Ordóñez, 2013; Santamouris et al., 2012): Vegetation, high albedo and water body.

Vegetation, i.e. the green space, can moderate climate mainly through the combined effect of (a) shading, which lowers the air and surface temperatures through interception of incoming solar radiation; (b) evapotranspiration, which requires significant amount of heat taken from surroundings (Gago et al., 2013). It has been found that urban greening contributes a lot to heat mitigation under various climates, even in subtropical and tropical climatic conditions. Through field measurement and microclimate modelling, Ng, Chen, Wang, and Yuan (2012) found that the pedestrian air temperature could be reduced by around 1 °C when the tree planting coverage area reached 33% of the site in Hong Kong. By the similar methodology, Srivanit and Hokao (2013) found that the average daily maximum temperature would be decreased by 2.27 °C at the pedestrian level when the quantity of trees was increased by 20% in a university campus in Japan. Wong et al. (2007) indicated that the peak temperature difference between dense, less dense and sparse greenery area could be as high as 4 °C in Singapore via field measurement. However, most of the previous studies only focused on the cooling effect in air temperature T_a. Its effect on human-biometeorological aspect has only been addressed in a few studies (Lee, Mayer, & Chen, 2016; Yahia & Johansson, 2014). Previous study demonstrates that green coverage ratio may be closely related to its mitigation potential (Gago et al., 2013). In addition, Givoni (1989) claimed that the type and features of the plant can affect

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cooling effect. Leaf area index (LAI) is a conceptual modelling parameter in studying plant's heat exchange with environment, and serves as a key measure in comparing plant canopies (Fahmy, Sharples, & Yahiya, 2010). Kotzen (2003) concluded that trees with low and high LAI could bring only 21% and 7% radiant heat underneath the canopy, respectively.

High albedo, another heat mitigation measure, is a key thermal property and an important indicator of the reflecting power of a surface. Corresponding to lower solar radiation absorption, high albedo materials gains lower surface temperature, which would lead to lower ambient temperature through the mechanism of convection (Santamouris, 2013). A few studies are available about investigating the cooling potential of pavement albedo increased. Takahashi (2011) found that if high albedo pavements were applied at the central area of Tokyo, the mean T_a might be reduced by 0.15 °C and even down to 0.6 °C by simulation. However, it might result in negative consequence on human thermal comfort. Through an experiment, Taleghani, Sailor, Tenpierik, and Van den Dobbelsteen (2014) concluded that increasing the albedo of pavement from 0.37 to 0.91 resulted in 1.3 °C decrease of T_a, but 2.9 °C rise of the mean radiant temperature T_{mrt}. In fact, T_{mrt} is an important factor to determine thermal comfort (Ali-Toudert, 2005). The cooling benefit in reducing T_a but negative impact on T_{mrt} would make an uncertain condition of thermal comfort. Indeed, besides albedo, the coverage ratio of high albedo materials (Santamouris, 2013) may be another important factor for heat mitigation.

Water body, a natural heat sink, has been used as a design tool by urban planners and architects to regulate the urban temperature. The associated cooling benefit originates from the enhanced evaporation of the water body during daytime and the high heat capacity (Coutts, Tapper, Beringer, Loughnan, & Demuzere, 2013). Using the 5-year climate data and the results of three measurement campaigns carried out in Bilbao, Acero, Arrizabalaga, Kupski, and Katzschner (2012) verified that rivers crossing urban areas were helpful in lowering air temperatures. Moreover, with the aid of advanced statistics of weather data and geographical information system (GIS), Radhi, Fikry, and Sharples (2013) found that lack of water could result in 2–3 °C increase of T_a in the city under the hot and arid climate. Taleghani, Tenpierik, Dobbelsteen, and Sailor (2014) evaluated water installations as heat buffer in Netherlands, using a water pool embedded on 65% of the ground inside a courtyard. The simulated results by ENVI-met showed that T_{mrt} was reduced in a range of 18–21 °C inside the courtyard with different orientations. However, Steeneveld, Koopmans, Heusinkveld, and Theeuwes (2014) had an opposite view. Through analysis of weather observations, they concluded that the water body increased 95% of the daily maximum UHI and might exert negative influence on human thermal comfort.

Through the literature review, it is found that HMSs based on landscape design were generally evaluated in terms of combating heat islands, not commonly from the human-biometeorological perspective. The human perception of heat and condition of thermal comfort are governed by the integral effect of thermo-physiological process, which are combined in the human heat balance. To date, many integrative thermal indices for thermal comfort assessment have been developed, and the Physiological Equivalent Temperature *PET* has been widely used to evaluate the effect of urban design on outdoor thermal comfort (Acero & Herranz-Pascual, 2015; Chen & Ng, 2012; Höppe, 1999; Lee et al., 2016; Ng & Cheng, 2012). Since only T_a is generally applied to evaluate the cooling benefit in the previous studies, *PET* should be introduced to evaluate the human-biometeorological aspect. On the other hand, the cooling potential of HMS is generally evaluated in a singular landscape design, like vegetation, albedo or water body only. An integrated implementation of various designs for HMS has not been considered. Among those three common measures of HMS, comparison of their effectiveness has not been carried out. As a result, this study would focus on the deficiencies as identified in the literature review, and the primary research objective is to consolidate and characterize the cooling potentials of various HMSs for landscape from both aspects of combating heat island and alleviating human heat stress. Possible parameters governing the heat mitigation potential of the strategies will be explored. Design insights and recommendations will be proposed for heat mitigation of UHI and/or human heat stress for open space.

As the first part of this study, this paper mainly deals with the investigation of thermal performance of different HMSs in landscape of real urban environment, and the evaluation of the model performance. Hence, the field measurement and modelling were presented.

2. Methodology

The methods used in this study consist of field measurement and numerical simulation. Field measurement was designed to collect the microclimate conditions and used for model validation. An open space simulation model was then established to conduct parametric study of different HMSs, which will be presented in Part II of this study.

2.1. Field measurement

Hong Kong is located in the southeast coast of China, with latitude of 22°15′ N and longitude of 114°10′ E. It has a monsoon-influenced humid-subtropical climate. City University of Hong Kong (CityU) was selected as the field measurement site, since such an institutional campus can be regarded as a small city due to its relatively large coverage. Its diverse landscape features and complex microclimates offer a valuable opportunity to investigate the multiple HMSs of landscape design. The observation points distribute around the spaces in various landscape forms among building blocks. The selected measurement locations are presented in Fig. 1, and the corresponding landscape environments are described in Table 1.

The field measurements were carried out from 10:00 to 22:00 local time in August 2015. All the measurements lasted for three days, and one day data were selected for analysis. Such day was selected according to weather type over a 24-h period (i.e. cloudy or clear days), data accuracy and reliability. As a typical summer sunny day, the data collected on 5th August was applied in this study. Basic meteorological data are described in Fig. 2, the hourly data of air temperature and relative humidity were derived from the Kowloon City weather station (nearby CityU), whist the hourly solar radiation, wind speed and direction data were retrieved from Hong Kong Observatory (HKO). It is observed that the weather on a typical summer sunny day can be characterized by high temperature, strong solar radiation and light wind conditions.

2.1.1. Collection of meteorological data

For the meteorological data, dry bulb air temperature T_a, wet bulb air temperature T_{wa}, globe temperature T_g and wind speed V were collected. In the field measurement, there were two kinds of arrangement: fixed and mobile measurements. Fixed measurement would be arranged as far as possible, but for those locations with frequently travelling people, mobile measurement was adopted. The equipment set-ups for the fixed and mobile measurements are shown in Fig. 3, and the technical specifications are described in Table 2. All the fixed and mobile measurement stations were configured and calibrated as per user manuals. Moreover, all sets of equipment were placed at the same location of outdoor environment to check their consistency and validity before use.

The measurement duration for fixed testing locations (L1, L6, L9 and L10) lasted for 12 h, and all data were collected at an interval of 1 s. The other six locations were covered by mobile measurements with three identical sets of equipment. It was carried out 15 min per hour in each location. Then it took 10 min for shifting equipment between the measurement points and 5 min for stabilizing equipment before measurement. In such measurement period, the data of T_{wa} and T_g were recorded at 1-min interval, the others were kept at 1-s interval. Those