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Potentials of meteorological characteristics and synoptic conditions to mitigate urban heat island effects

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ABSTRACT

Urban heat island (UHI) has been evidenced as a phenomenon having a series of negative consequences in energy use, human thermal comfort, citizens' health, wellbeing and air quality. Thus, all professions, faculties and disciplines of society are actively seeking for effective UHI mitigation techniques and strategies. Previous studies have indicated that synoptic variables such as wind, precipitation, cloud coverage, fog and air quality have significant impacts on UHI phenomenon. In accordance with this basis, we devise to develop UHI mitigation techniques and strategies based on meteorological characteristics and synoptic conditions. This paper therefore has reviewed the influences of meteorological characteristics and synoptic conditions, such as precipitation, wind, cloud coverage, fog, air pollution and haze on UHI effects. Through this work, people can obtain better understandings of using them to mitigate UHI effects. Meanwhile, some suggestions on urban planning and development have been briefly presented for the alleviation of UHI effects.

1. Introduction

Accompanying with global warming and accelerated urbanization, many cities are undergoing great sprawls and structural changes, resulting in a special phenomenon that urban temperatures are significantly higher than suburban or rural temperatures (Zhao et al., 2017). This is entitled as urban heat island (UHI) phenomenon. UHI effects have been well documented as a consequence of anthropogenic activities, posing significant challenges to urban systems, inhabitants' living and ecosystems. For cities that are located in high-altitude regions or in colder seasons (e.g. Changchun of China, Barrow, Alaska of the US, Norilsk of Russia), UHI effects can somewhat reduce energy use for heating (Yang et al., 2017; Hinkel et al., 2003; Varentsov et al., 2014), however, most studies have verified that UHI leads to a dramatic increase of energy consumption for cooling in hot summer. In parallel, UHI effects have brought adverse impacts on urban thermal environment, outdoor thermal comfort, human health and wellbeing, and air quality (Yow, 2007; Santamouris, 2016).

In the context of urban development, UHI is currently and will be still a great challenge for the world. It is estimated that > 1100 cities around the world are suffering from UHI effects, regardless of latitude, altitude, scale and size, and climatic condition of cities (Stewart, 2011). Given the urbanization, only have 54% of the global population lived in urban areas until 2014, and its level is projected to reach 66% in 2050 (United Nations, 2014). An increasing urban population means intensified anthropogenic activities, and the number of cities will continue to grow rapidly in the future. Consequently, this will aggravate UHI effects in both intensity and city number. Therefore, it is imperative to explore effective UHI mitigation techniques and strategies.

From the perspective of energy balance in urban areas, mechanism that many techniques and strategies can mitigate UHI effects lies in weakening heat source strength and promoting excess urban heat dissipation. Cool materials that are characterized by features

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of high solar reflectance and high infrared emittance, for instance, could be painted or assembled on the surface of building rooftops and pavements, to reduce the absorption of solar radiation and improve the ability of reflect solar radiation, for the final reduction of energy inputs. Because of transpiration and evaporation, well-built urban green spaces, green rooftops and permeable materials are capable to promote heat decrease. Urban heats derived from anthropogenic activities should be controlled and excess heats are expected to be dissipated effectively (Santamouris, 2016).

In past decades, numerous studies have been carried out to hunt for effective UHI mitigation techniques and strategies. Fortunately, many of them such as cool materials, greenery systems and water bodies, have been applied in practices. However, these techniques as well as their contributions to urban temperature reduction are sometimes constricted (Santamouris et al., 2016). As a result, many scholars divert their attention to and draw support other disciplines, for creating a holistic UHI mitigation system. Previous literatures have evidenced that wind speed and wind direction have significant effects on UHI intensity and spatial distribution. At the same time, UHI intensity decreases with the increase of wind speed and cloud coverage amount. Some scholars have already made attempts to use wind to mitigate UHI effects in Hong Kong, Germany cities and Japanese cities (Kress, 1979; Architectural Institute of Japan, 2008; Wong et al., 2010). Additionally, other factors such as precipitation, fog and air quality can also exert influences on UHI effects, which can be potentially utilized in future UHI mitigation. Based on the influence of above-mentioned meteorological characteristics and synoptic conditions (MCSC) on UHI, this paper initially proposes to develop their potentials to mitigate UHI effects, although this method is currently not mature for the limited studies concerning the impacts of MCSC on UHI intensity and spatial distributions.

To provide a better understanding of the context of using MCSC-based UHI mitigation strategies and to support this method, this paper is designed to collect evidence on the impacts of MCSC on UHI in previous literatures. In the following sections, this paper has analyzed several factors like precipitation, wind, cloud coverage, fog, air quality and haze, respectively. Afterwards, some suggestions on how to adopt these influences for UHI mitigation during urban development and planning have been presented. The idea in this paper is expected to provide urban planners and policy makers with more possible approaches to cope with UHI problems.

2. Influence of precipitation on UHI effects

It is widely evidenced that during the process of precipitation, urban temperature could be reduced and then consequently a reduction of temperature difference between urban-rural areas and a lowered UHI intensity could be observed. Based on the meteorological data of Singapore from 1872 to 1988, Chow and Roth (2006) investigated relationships between monthly precipitation and monthly temperature and indicated that higher monthly mean temperatures corresponded strictly to reductions of monthly mean precipitation. This result is in good agreement with Arifwidodo and Tanaka's research on impacts of precipitation on UHI effects in Bangkok, Thailand. They pointed out that during rainy season from May to October, precipitation should be considered as one of the main controls for UHI effects. The maximum precipitation in August corresponded to the weakest UHI intensity of 2 K, while UHI effects would be exacerbated to 5 K once precipitation reduced to zero in December (Arifwidodo and Tanaka, 2015). Based on field observation and experience, it is concluded that UHI intensity increases by 0.0021 K for every 1 mm reduction in annual precipitation. That means a city will suffer from an intensified UHI of 1.1 K if its precipitation reduces by 500 mm (Zhao et al., 2014).

Influence of precipitation on UHI effects varies with seasonal conditions. Through investigating UHI effects in Beijing, China throughout a year, Liu (2014) comparatively analyzed the UHI phenomenon under precipitation and no precipitation conditions. Results indicated that UHI mitigation capacities of precipitation in four seasons were overall higher than 1 K. The precipitation exerted the smallest influence on winter UHI effects, while precipitation had the most significant impacts on autumn UHI effects, in which season the city even experienced cool island phenomenon. Meanwhile, Wang et al. (2016) also analyzed what role precipitation in Jining, China could play in affecting UHI effects. Likewise, precipitation generated the weakest influence on winter UHI effects, however precipitation performed its largest mitigation effects on summer UHI effects rather than autumn ones. This is in consistence with the results obtained by Wang et al. (2009), who investigated the effects of precipitation on Langfang UHI effects. Overall, precipitation has the greatest effects on summer and autumn UHI effects, even sometimes, cool island effects are dominant, while although it does relatively lower effects on spring and winter UHI effects, UHI intensity has also fallen to low levels.

The impacts of precipitation on UHI effects show a trend of diurnal and nocturnal variation. Wang et al. (2009) observed that during the process of precipitation in Langfang, China, the most intensified UHI occurred at 1:00, while the weakest one occurred at 12:00. Comparatively, the weakest UHI of Shengyang, China during the precipitation emerged at 14:00, while precipitation made its smallest influence at 20:00, corresponding to the most intensified UHI intensity (Li et al., 2011). The same studies conducted in Jining, China have also evidenced their results (Wang et al., 2016). During precipitation period in a day, UHI generally had a pattern of intensified nocturnal UHI effects and weakened diurnal UHI effects, and UHI effects at 12:00–14:00 were the weakest.

Previous scholars have attempted to explain the mechanism of how precipitation leads to UHI variations. It is commonly recognized that increase of cloud coverage before and after rain, and evaporation of rainwater after precipitation process that takes away urban sensible and latent heats have correlations to UHI intensity reduction (Jauregui, 1997; Yu et al., 2009; Li et al., 2011). During rainy season of Mexico City, Jauregui (1997) field observed UHI variations before, during and after raining and pointed out that (1) Before raining: only when cloudiness increased to a certain level could UHI effects start to be alleviated. (2) During raining: UHI effects were suddenly weakened when the city was hit by torrential rains, while the UHI effects still maintained at a certain level. (3) After raining: with the process that ground sensible surface heats was neutralized by cooler rainwater and evaporated in the form of latent heats, urban temperature continued to reduce to zero and even negative. However, UHI intensity was the lowest during raining period, after which UHI shown a gradual upward trend when analyzing the relationships between UHI effects and precipitation (Liu, 2014). Along with time series of before, during and after raining, UHI effects followed generally an obvious "V"

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