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Approaches to study Urban Heat Island – Abilities and limitations

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ABSTRACT

Urban Heat Island (UHI) has significant impacts on the buildings energy consumption and outdoor air quality (OAQ). Various approaches, including observation and simulation techniques, have been proposed to understand the causes of UHI formation and to find the corresponding mitigation strategies. However, the causes of UHI are not the same in different climates or city features. Thus, general conclusion cannot be made based on limited monitoring data.

With recent progress in computational tools, simulation methods have been used to study UHI. These approaches, however, are also not able to cover all the phenomena that simultaneously contribute to the formation of UHI. The shortcomings are mostly attributed to the weakness of the theories and computational cost.

This paper presents a review of the techniques used to study UHI. The abilities and limitations of each approach for the investigation of UHI mitigation and prediction are discussed. Treatment of important parameters including latent, sensible, storage, and anthropogenic heat in addition to treatment of radiation, effect of trees and pond, and boundary condition to simulate UHI is also presented. Finally, this paper discusses the application of integration approach as a future opportunity.

1. Introduction

The growth of world urbanization has been extensively accelerated since the Second World War. According to the Population Reference Bureau [55], 50% of the world population (3.4 Billion) is settled in urban areas. Also, it is predicted that inhabitation in cities will reach 60% (5.0 Billion) by 2030 which means around two billion more people will reside inside cities by that year. In addition, the number of cities with population of over one million is expected to increase by approximately 100 from 2005 to 2015 [55]. Massive building construction is underway to respond to this overwhelming dwelling demand. This excessive and unplanned growth of urbanization has caused undesired side effects around the world. Urban Heat Island (UHI) as a consequence of urbanization [50] was first documented by Howard in 1818. Summertime UHI considerably decreases the outdoor air quality (OAQ) as well as increasing the energy demand of a city, and as a consequence of this energy increase, widespread power outage may occur due to the increase of the air conditioning system usage. Thousands of deaths are annually reported due to the heat related illnesses, and the most recent example is the severe heat wave contributed to death of around 50,000 people in Europe, in August 2003. Apart from the effect of temperature and electricity consumption, UHI also intensifies pollutant concentration over urban areas [63]. Furthermore, it impacts the local meteorology by altering local wind patterns, forming cloud and fog, increasing humidity, and changing the precipitation rate [68].

The behaviour of artificial urban texture in terms of absorption of short-wave and long-wave radiation, transpiration, releasing of anthropogenic heat, and blocking prevalent wind is significantly different from that of the rudimentary nature. The urban energy budget was first proposed by Ref. [47] within a city as follows:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \quad (1)$$

where Q^* is the net radiation, Q_H and Q_E are the fluxes of the sensible and latent heat, respectively, Q_F represents the anthropogenic energy release within the control volume, ΔQ_A is the net advection through the lateral sides of the control volume, and ΔQ_S is the storage heat flux and represents all energy storage mechanisms within elements of the control volume, including air, trees, building fabrics, and soil. Also, the energy balance for each facet of this control volume was expressed as bellow:

$$Q^* = Q_H + Q_E + Q_G \quad (2)$$

where Q_G is the conductive heat flux.

Since the parameters in equations (1) and (2) are functions of city location and characteristics, it can be concluded that the energy

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balance inside a city alters when these parameters varies. This means that UHI intensity is not spatially and temporally similar in different cities. For instance, radiation absorption can be a dominant factor for diurnal UHI in equatorial climate, especially when the sky is calm and cloudless. However, anthropogenic heat release can be the main cause of nocturnal UHI in high-rise and dense metropolitan areas when the sky is cloudy.

The most effective approaches to mitigate UHI include increasing materials' albedo in a city, increasing vegetations, trees, and ponds within urban areas, reducing released of anthropogenic heat inside building canopies, and designing canopies and buildings. These strategies have a direct and an indirect effect on energy consumption and OAQ of a city [2].

This paper first will review the existing approaches in UHI studies and then outlines the limitations of each technique. Furthermore, this paper summarizes developed tools for predicting and mitigating UHI. Finally, the prospective of the UHI study will be discussed.

2. Techniques to study the urban heat island

2.1. Multi-scale phenomena

UHI formation is the consequence of several phenomena, including small-scale processes like human metabolism and meso-scale interactions like atmospheric forces. Therefore, different resolutions are required to integrate all these aspects simultaneously. However, this is not a feasible approach due to complexities in providing a comprehensive database for a city and also due to the weakness of existing theories in describing the corresponding phenomena in each scale. Because of these limitations, a number of simplifying assumptions are made in the development of the existing approaches: this is the main cause of discrepancy in UHI results.

To reduce the above mentioned discrepancy, therefore, it is important first to emphasize the significant terms in equation (1) based on the scale of study. For example, atmospheric reactions (e.g. Coriolis force) are important in meso-scale studies, even though these terms are negligible in canopy-scale problems. On the contrary, anthropogenic heat release from human body is an important parameter in building-scale topic, while it could be insignificant parameter in meso-scale studies. The significance of a parameter in a study is usually expressed by corresponding dimensionless numbers. For instance, the ratio of inertial to Coriolis forces – called Rossby number – is widely used in meso-scale topics, and the Richardson number, representing the ratio of the natural convection to the forced convection is used in canopy-scale studies. Observation and/or theoretical approaches have used to investigate the UHI phenomena.

2.2. Observational approaches

In recent years, many general observations have been made in accordance to the geographic scope used in heat island studies. Arnfield [5] summarizes them as follows: UHI intensity decreases with increasing wind speed; UHI intensity decreases with increasing cloud cover; UHI intensity is more severe during summer or warm half of the year; UHI intensity tends to increase with increasing city size and population; and UHI intensity is greatest at night. However, the above conclusions have contradicted by other studies. For example, maximum UHI intensities were found for sunny days in Saskatoon under clear and calm condition [59]. Also, negative heat island intensity (rural area warmer than urban area) was reported in Reykjavik [67]. These contradictions are related to weakness of statistical analysis to present several physical phenomena (see equation (1)).

2.2.1. Field measurement

In the field measurement approach, the near surface temperature pattern in urban area is generally compared with rural area. This involves the analysis of statistics on urban–rural differences based on pairs of fixed or mobile stations or groups of stations [5]. Field measurement was first used to study UHI by Howard in 1818 for the City of London. Since then, many monitoring researches have been reported in different cities [30]. Results have been mostly used to find spatial distribution and intensity of the heat island inside a city. The numbers of stations, the impact of climate, and the method of comparison have been summarized by Arnfield [5]. Santamouris [62] also reviewed observational studies of UHI, specifically for European cities. With the advancement of measurement devices, other parameters like air velocity, turbulence fluctuations and pollution concentration have been also measured, in order to find correlations between these parameters and UHI intensity.

Despite this, one should note that field measurement, as an independent approach, has several limitations. The development and installation of measurement devices around a city are generally very expensive and time-consuming task. In addition, limited stationary network or mobile stations is generally used, and only a limited number of parameters are simultaneously measured. This implies that it is not possible to demonstrate all the three-dimensional spatial distribution of the quantities inside an urban area. Instead, approximations are frequently made to estimate these quantities for inaccessible points. In addition to these shortcomings, it is necessary to carry out the measurements for a long period of time to filter the effect of unpredictable errors (e.g. vehicles and pedestrians). Finally, data analysis is the weakest point of this approach. Even after collecting sufficient data, consistent generalizations cannot be made with simple correlations between measurements and UHI characteristics, because of the abundance of parameters that could influence the UHI formation.

In addition, some investigations used measured data for the validation of mathematical models or boundary condition settings in simulation schemes [72]. Nunez and Oke [47] measured the radiation fluxes, air velocity and temperature which were later used in an urban canopy model.

2.2.2. Thermal remote sensing

With the advancement of sensor technology, thermal remote observation of UHI became possible through the use of satellite, airborne and aircraft platforms. The resultant surface temperature contains the effects of surface radiative and thermodynamic properties, including surface moisture, surface emissivity, surface albedo, the irradiative input at the surface, and the effects of the near surface atmosphere, in addition to the turbulent transfer from the surface [8]. The applications of thermal remote sensing to assess UHI intensity distribution were reviewed by Voogt and Oke [75].

It should be noted that remote sensing is a very expensive approach, and it is not possible to have steady images from the urban surface. This is partly related to the capability of the used apparatuses and partly due to the atmospheric interactions. For example, satellites, which revolve around earth, spend a limited time over one specific region, and there is always a probability of cloudy sky when the satellite images capture the UHI over a land. The main technical concern in this approach is nonetheless that the surface temperature measured by sensors only relates to the spatial patterns of upward thermal radiance received by the remote sensor [75]. However, the surface UHI is different from the atmospheric UHI in which turbulence and velocity activities have impact on the ambient air temperature. This means that observed surface temperature can be significantly different from the ambient air temperature inside street canyons. Therefore, in order to fully use the measured data, it