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A review on the generation, determination and mitigation of Urban Heat Island

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Abstract

Urban Heat Island (UHI) is considered as one of the major problems in the 21st century posed to human beings as a result of urbanization and industrialization of human civilization. The large amount of heat generated from urban structures, as they consume and re-radiate solar radiations, and from the anthropogenic heat sources are the main causes of UHI. The two heat sources increase the temperatures of an urban area as compared to its surroundings, which is known as Urban Heat Island Intensity (UHII). The problem is even worse in cities or metropolises with large population and extensive economic activities. The estimated three billion people living in the urban areas in the world are directly exposed to the problem, which will be increased significantly in the near future. Due to the severity of the problem, vast research effort has been dedicated and a wide range of literature is available for the subject. The literature available in this area includes the latest research approaches, concepts, methodologies, latest investigation tools and mitigation measures. This study was carried out to review and summarize this research area through an investigation of the most important feature of UHI. It was concluded that the heat re-radiated by the urban structures plays the most important role which should be investigated in details to study urban heating especially the UHI. It was also concluded that the future research should be focused on design and planning parameters for reducing the effects of urban heat island and ultimately living in a better environment.

Key words: urban heat island (UHI); urbanization; temperature rise; mitigation

Introduction

Urbanization and industrialization improve our material lives and comfort; however, they also induce many problems to human beings, such as global warming, industrial waste, and air pollution. Apart from the adverse global impacts, they affect regional urban areas more seriously and obviously where industrial activities and heavy use of synthetic construction material are commonly observed. As a result, the natural environment and ecology are tremendously affected and have lost necessary balance. More people are vulnerable to urbanization problems as the ever increasing urban population, which was estimated as 48% or three billion, is expected to be five billion by 2030 (World Urbanization Prospectus, 2004). Two major phenomena were observed in large cities as compared to its surroundings: a higher temperature or heat content called Urban Heat Island (UHI) and an occasional lower temperature called Urban Cool Island (UCI) or Urban Cool Valley (UCV). Higher urban heat is mainly caused due to the anthropogenic heat released from vehicles, power plants, air conditioners and other heat sources, and due to the heat stored and re-radiated by massive and complex urban structures. Huge quantities of solar radiations are mainly stored and re-radiated in urban areas due to massive construction material and decreased sky view factor. The urban areas also posses less vegetation due to its typical land use. High roughness structure is another problem of urban areas which reduces the convective heat removal. It has been suggested to reduce anthropogenic heat release and make proper design changes such as the use of high albedo, cooler roofs, suitable building material, and proper building design to reduce high heat intensity due to the above mentioned problems.

The adverse effects of UHI includes the deterioration of living environment, increase in energy consumption (Konopacki and Akbari, 2002), elevation in ground-level ozone (Rosenfeld *et al*., 1998) and even an increase in mortality rates (Changnon *et al*., 1996). The field of UHI has become highly interesting for scientists and engineers due to its adverse environmental and economic impacts on the society and promising benefits associated with mitigating high heat intensity. A review of relevant literature revealed that planting more vegetation has widely been reported as a promising mitigating measure (Tong *et al*., 2005; Ca *et al*., 1998; Ashie *et al*., 1999; Yu and Hien, 2006) though the proposed mitigating measures cover many other areas. Konopacki and Akbari (2002) reported that by mitigating UHI effects in Houston it was possible to achieve savings of USD 82 million with a reduction of 730 MW peak power, together with an annual decrease of 170000 t of

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carbon emission. Rosenfeld *et al*. (1998) reported that ozone level could exceed 120 ppbv at 22°C and could reach 240 ppbv at 32°C. They used numerical simulation and predicted an annual reduction of 25 GW of electrical power or potential savings of USD 5 billion for the US by year 2015. It might be because the possible benefits of reducing UHI are enormous, the research community has carried out vast research work in this field and therefore large amount of literature are available. However, due to the complicated conditions of typical cities, simple methods are rarely available on understanding, quantifying and mitigating UHI. This paper aims at presenting a review of the available literature on the generation, determination and mitigation of UHI in the light of summarizing the most valuable findings, presenting the problem in the most convenient way and discussing the potential future research areas.

1 Generation of Urban Heat Island

UHI is the mutual response of many factors which could broadly be categorized as controllable and uncontrollable factors as shown in Fig.1. The controllable and uncontrollable factors could further be categorized as the temporary effect variables, such as air speed and cloud cover, permanent effect variables such as green areas, building material, and sky view factor and cyclic effect variables such as solar radiations and anthropogenic heat sources. The heat generated and contained in an area comes from the sun in the form of solar radiations and from power plants, automobiles, air-conditioners and other sources as anthropogenic heat. Almost all anthropogenic heat enters into the environment instantly and directly. On the other hand, only part of solar radiations heat up the environment directly, the rest are absorbed by the complicated urban built structures and heat up the environment indirectly. The basic heat transfer and energy conservation processes, such as conduction, convection and radiation play their characteristic roles in this heat exchange. The structures on ground level, such as walls and roof facets, irrigated gardens, non-irrigated green spaces, lawns and paved areas etc. capture solar radiation to different extents. These natural and man-made structures continuously absorb and store this radiation in the form of heat energy from sunrise till late afternoon. Afterwards, the sun starts setting aside and the environment starts cooling down. The heat energy stored in structures is then released to the environment. The method and quantity of heat released by the urban structures, however, depends on other controllable factors such as the sky view factor and building material. In a typical urban area, massive construction material is placed within a very small space that captures high intensity of solar radiation. The ability of heat release by long-wave radiation in cities is low due to decreased sky view which results in high heat storage in building structures. It is believed that the albedo, the reflected light in comparison to the incident light, is also very low in cities due to typical street canyon configurations, and is one of the main reasons of high air temperatures. The design values of albedo and sky view factor are, therefore, reported as two important factors in creating UHI (Giridharan *et al*., 2004). Due to the lack of vegetation cities also exhibit little latent heat of vaporization. It was reported that evapotranspiration in Tokyo has been reduced by 38% from 1972 to 1995 (Kondoh and Nishiyama, 1999). High roughness of structures in urban areas reduces the amount of convective heat removal and transfer by wind. Typical thermal properties of building materials used in urban areas, such as low admittance, are other potential contributors. It is also believed that air pollutants, in particular aerosols that are abundant over polluted urban areas, can absorb and re-radiate long wave radiation and inhibit the corresponding radiative surface cooling producing a pseudo-greenhouse effect, which are responsible for causing UHI.

UHI has also been reported to be affected by temporary effect variables in certain ways. Pongracz *et al*. (2006) reported that anticyclone conditions increase Urban Heat Island Intensity (UHII). Many studies have reported the influence of wind speed and cloud cover on UHI, the results show that the UHI is negatively correlated with wind speed and cloud cover (Kim and Baik, 2005; Oke, 1982). On the other hand, the UHI has been reported to be positively correlated with the city population. Hung *et al*. (2005) have studied UHI in twelve Asian mega cities and reported that the magnitude and extent of the UHI was positively correlated with city population. Kim and Baik

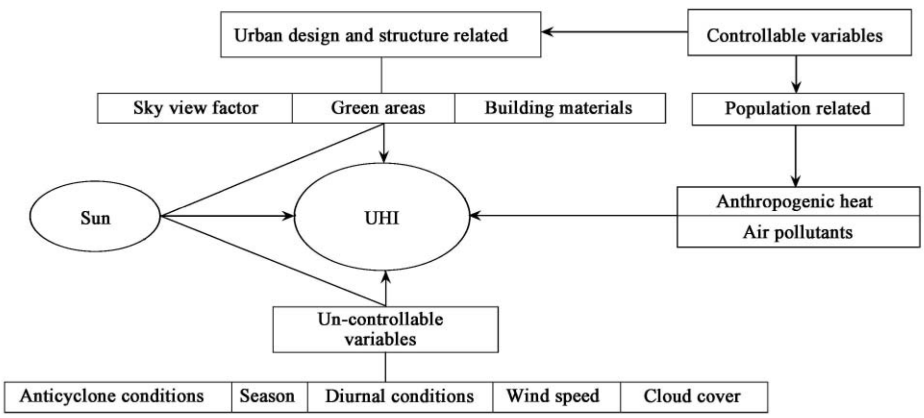

Fig. 1 Generation of Urban Heat Island (UHI).

(2004), on the other hand, did not found it related with population. Hung *et al*. (2005) have observed maximum UHII of 8°C in Bangkok with a population of 11 million and maximum UHII of 7°C with a population density of 12.55 million in Shanghai. They have also reported maximum UHII of 7°C in Manila with a population density of 15617 (persons/km^2) and maximum UHII of 12°C with a population density of only 6218 (persons/km^2) in Tokyo. The population could have twofold effects on heat generation, a direct effect as more people means more metabolisms and an indirect effect as number of buildings, vehicles, factories etc. will likely be increased with the increasing population. However, other variables such as sky view factor, anthropogenic heat, building design and material etc. do play an important part in increasing heat contents. These factors are not population dependent and may or may not favor in increasing the heat contents with increased population. Therefore population (population density might be a better term) could, but not necessarily, increase the heat contents of an area. As the UHI would be a mutual response of many factors which includes the population, a comparison should take into account all controllable factors and should not be limited to population or any other factor. A comparison of controllable factors and the relevant UHII of different areas might help quantify the significance of the important factors, i.e. the sensitivity of individual variables on UHI. There has been some research on quantifying the significance of temporary effect variables; an example is the study conducted by Kim and Baik (2002) who reported that a decrease in maximum UHI could be visible with wind speed greater than 0.8 m/s while with critical wind speed of 7.0 m/s maximum UHII of 0.3°C or less could vanish. In another study Klysik and Fortuniak (1999) reported that an UHI of higher than 1°C could still be observed when the city average wind speed is 4 m/s during night time and 2 m/s during day time. Morris *et al*. (2001) reported that the UHII is approximately the fourth root of both the wind speed and cloud cover. Yet, more work is required in developing the degree of influence of various temporary and permanent factors on UHI.

2 Determination of Urban Heat Island

UHII is an important indicator of evaluating the severity of the urbanization of an area. However, it puts little light on the heat generated by various heat generating sources. The Surface Energy Balance (SEB), which gives an idea of the heat generated and contained by an area, could help understanding the heat generated by various sources. The UHII, SEB and the important supporting techniques used in determining the UHII and SEB will be discussed in detail in the following sections.

2.1 Urban Heat Island Intensity

UHII is determined as the spatially-averaged temperature difference between an urban and its surrounding rural area (Magee *et al*., 1999; Kim and Baik, 2005). This concept, however, covers a range of diversified ideas that include the temperature difference between the well developed urban area and least developed area or between two different built-up areas. Wong and Yu (2005) reported a maximum UHII of 4°C in between the well planted and the most built-up region of central business district in Singapore. Giridharan *et al*. (2004, 2005) reported UHII of magnitude as low as 0.4°C and as high as 1.5°C within and in between three housing estates in Hong Kong. The reported UHIIs have been based on the difference between air and surface temperatures, both of whom have shown different trends. It was reported that the UHIIs were high during night time or early morning and low in day time (Kim and Baik, 2005; Jauregui, 1997; Lemonsu and Masson, 2002; Montavez *et al*., 2000; Klysik and Fortuniak, 1999). The reported UHII varies from area to area and method to method. Saitoh *et al*. (1995) have collected weather data using an automobile and reported the surface-temperature based UHII of 8°C in Tokyo while Hung *et al*. (2005) have used satellite data to report maximum surface-temperature based UHII of 12°C in Tokyo. Hafner and Kidder (1999) have modeled and reported the surface-temperature based UHII of 1.2°C and air temperature based UHII of only 0.6°C in Atlanta, USA. Kim and Baik (2005) using weather station data, reported maximum air-temperature based UHII of 3.4°C in Seoul while Hung *et al*. (2005) reported the surface-temperature based UHII of 8°C in Seoul using satellite data. Magee *et al*. (1999) reported air-temperature based maximum UHII of 1°C in Fairbanks, Alaska, while Klysik and Fortuniak (1999) reported air-temperature based maximum UHII of 12°C in Poland, both using weather station data. The results of the above studies are summarized as four different cases in Table 1.

The UHII determined by comparing the mean and maximum temperature in between urban and rural areas are referred to as the mean and maximum UHII respectively. The comparison time period used to be a season, a month, or a year, or in some cases using few selected days (Velazquez-Lozada *et al*., 2006). The selected days usually consists of clear and quiet nights that minimize the effects of temporary effect variables. Most of the yearly based analyses have also reported maximum temperature difference in clear and quiet nights which also supports the selection criteria (Kim and Baik, 2004, 2005). Although, the UHII has been defined as the temperature difference between urban and rural areas, it has also been reported as the temperature change over time. In one of such studies UHII was determined in Tokyo as the temperature change from 1930 to 1990 (Mochida *et al*., 1997). In another approach the average present time temperature was subtracted from the average past time temperature for both urban and rural areas and the difference of the changed temperature is then reported as UHII (Magee *et al*., 1999).

2.2 Source heats

The heat generated by and contained in an area could be given as SEB equation as given below (Oke, 1988):

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A \tag{1}$$

Table 1 Four cases of varying UHII with respect to area, method and type

Area	Method	Type	UHII (°C)
Tokyo[a]	Automobile data collection	Surface-temperature	8.0
Tokyo[a]	Satellite data collection	Surface-temperature	12.0
Atlanta, USA[b]	Modeled	Surface-temperature	1.2
Atlanta, USA[b]	Modeled	Air-temperature	0.6
Seoul[c]	Weather	Station air-temperature	3.4
Seoul[a]	Satellite data	Surface temperature	8.0
Fairbanks[d]	Weather station	Air-temperature	1.0
Poland[d]	Weather station	Air-temperature	12.0

[a] The same area and type of UHII with different data collection method; [b] the same area and method of data collection with different type of UHII; [c] the same area with different method of data collection and type of UHII; [d] the different areas with the same method of data collection and type of UHII.

where, Q^* is the net all-wave radiation, Q_F, Q_E and Q_H are respectively the anthropogenic heat release, the turbulent sensible and turbulent latent heat flux densities, ΔQ_S is the sensible heat storage and ΔQ_A is the net heat advection.

2.2.1 Net all-wave radiation (Q^*)

This part of energy balance represents the short and long wave radiation captured by an area. Both types of the radiation could be measured using suitable measuring sensors, the net all-wave radiation could then be calculated as the difference in between the incoming and outgoing parts (Brotzge and Crawford, 2003; Christen and Vogt, 2004). The incoming short wave solar radiation was reported to be attenuated due to the heavy smoke over urban areas (Sang *et al*., 2000; Oke, 1988). The attenuation has been reported to be as high as 33% in some cases (Stanhill and Kamala, 1995) and has also been reported as a cause of Urban Cool Island (Sang *et al*., 2000). In some other areas, on the other hand, the attenuation has not been observed (Christen and Vogt, 2004). It is reported that the attenuation of incoming short wave radiation is compensated by albedo related drop in outgoing shortwave radiation and enhancement of incoming long wave radiation is compensated by an increase in outgoing long wave radiation due to the high surface temperature emittance. It was reported that most of the attenuated part is diffused and received back and the net difference between the urban and rural areas may not be more than 5% (Oke, 1982, 1988).

2.2.2 Turbulent heat fluxes

Turbulent heat fluxes comprise of the sensible and the latent heat flux, which could be directly derived from eddy correlation, measured using appropriate equipments. The heavily built urban areas are reported to be responsible for increased sensible heat flux which is reported to vary as per the built surface (Oke, 1988). The intensity of latent heat flux, on the other hand, varies from situation to situation as concluded by Hafner and Kidder (1999). Grimmond (1992) described the latent heat flux as the largest portion in the SEB while Masson (2000) has neglected it in his proposed town energy balance scheme. Although, it is likely that the latent heat flux will be low in an urbanized area due to decreased vegetation, it could be high in vegetated parts of the city. The study conducted by Suckling (1980) reported a Bowen Ratio, sensible-heat-flux-to-latent-heat-flux ratio, of up to 98% for a suburban lawn. It was reported that the turbulent heat fluxes vary with respect to the Q^* (Arnfield and Grimmond, 1998; Offerle *et al*., 2006). Thermal admittance and ground moisture availability are reported to be other important factors in quantifying the turbulent heat fluxes (Oke, 1988).

2.2.3 Subsurface (storage) heat flux

Christen and Vogt (2004) reported that due to the complicated configuration of surface materials, orientations and their interactions, the direct measurement of storage heat flux in an urbanized area is almost impossible. The term is, therefore, usually modeled or determined as the residual of the SEB equation. It is reported that an increase in the net all-wave radiation directly increases the stored heat flux. Grimmond (1992) found an increase of around 60% in the monthly averaged day-time ratio of stored heat flux to the net all-wave radiation with an increase of net all-wave radiation.

2.2.4 Net heat advection (ΔQ_A)

Net heat advection could be referred to as the inaccurate measurement due to spatial gradient in temperature, humidity and wind. It is suggested that the effects of advection could be negligible provided that caution has been taken in deciding the measurement height (Christen and Vogt, 2004).

2.2.5 Anthropogenic heat (Q_F)

Anthropogenic heat represents the heat generated from stationary and mobile sources of an area. It is reported that the Q_F must either be converted to radiations, sensible heat flux or latent heat flux or is stored (Christen and Vogt, 2004). This component has been modeled as the sum of heat generated by the buildings, vehicles and people (Sailor and Lu, 2004; Grimmond, 1992) or as the residual of other terms (Christen and Vogt, 2004). The reported values of this term vary greatly from area to area as summarized in Table 2. Christen and Vogt (2004) have reported anthropogenic heat of 5–20 W/m^2 for Basel, Switzerl, while Offerle *et al*. (2005) and Steinecke (1999) have reported anthropogenic heat of 32 and 35 W/m^2 from Lodz, Poland and Reykjavik, Iceland, respectively. Sailor and Lu (2004) have reported anthropogenic heat of 60 W/m^2 in summer and 75 W/m^2 in winter from six large cities of USA while Ichinose *et al*. (1999) reported 200 W/m^2 in summer and 400 W/m^2 in winter and the highest value of 1590 W/m^2 in Tokyo. Oke (1988) reported that anthropogenic heat release could be related to the

Table 2 Reported anthropogenic heats in various parts of the world

Residual of other terms method	Reported anthropogenic heat (W/m^2)	Reference
Basel, Switzerland	5–20	Christen and Vogt, 2004
Lodz, Poland	32	Offerle *et al*., 2005
Reykjavik, Iceland	35	Steinecke, 1999
USA	60–75	Sailor and Lu, 2004
Tokyo, Japan	200–1590	Ichinose *et al*., 1999

population and its per capita energy use. Taha (1997) reported that the anthropogenic heat has smaller effect than albedo and vegetation cover, and is negligible in commercial and residential areas. Offerle *et al*. (2006), on the other hand, have considered it as a significant input in winter. It seems that depending on the area and its energy use the term could be significant or negligible and it could have varying diurnal, seasonal or even weekly trends.

2.3 Supporting techniques

2.3.1 Space technology

Space technology has been successfully employed in determining the surface-temperature and SEB. Many studies have demonstrated the wide and versatile applications of space technology. An example is the study conducted by Voogt and Grimmond (2000) who have determined the sensible heat flux in Canada through remotely sensed surface-temperature. Kondoh and Nishiyama (1999) have studied the changes in evaporatization in Japan using space technology. The surface parameters, such as albedo, and soil properties, were determined by Hafner and Kidder (1999) using advanced very high resolution radiometer (AVHRR) satellite data. Nichol and Wong (2005) suggested a method for producing a complete and accurate picture of the urban thermal environment by taking into account all energy exchanging surfaces in Hong Kong.

2.3.2 Numerical modeling

Numerical modeling is another important supporting tool with a wide area of successful applications in studying UHI. The applications of this supporting tool varies and covers the determination of important influencing factors such as wind speed, anthropogenic heat release, and thermal properties such as albedo, sensible and latent heat. Lemonsu and Masson (2002) used numerical models and reported that conduction of heat in buildings is the most significant contributor in SEB. Arnfield and Grimmond (1998) also used numerical models and reported that the wall thermal properties and building height to separation ratio have the most important influence in SEB. Ashie *et al*. (1999) used numerical modeling techniques and reported that the artificial heat release by the air conditioners is 0.5°C along the building. Dupont *et al*. (2004) have determined the sensible and latent heat fluxes using numerical modeling. Yamda (2000) has generated albedo, roughness, anthropogenic heat release, and soil moisture distributions. Kato and Yamaguchi (2005) have reported the anthropogenic heat release trends. Takahashi *et al*. (2004) have predicted air temperature, heat flux and humidity. The model of Huang *et al*. (2005) could also predict temperature, humidity, and wind velocity. Lemonsu and Masson (2002) have modeled the temperature of four areas of Paris. Masson *et al*. (2000, 2002) have presented and validated a detailed energy budgeting scheme. Although the application of numerical modeling seems to cover a wide area, it is pointed out that the reliability of numerical models for urban climate estimation has not been thoroughly validated. In particular, surface properties have not been suitably incorporated into numerical models (Oke, 1988; Arnfield, 2003).

2.3.3 Small-scale physical models

In a comparatively less applicable technique, small-scale physical models have been used in studying the UHI and related urbanization factors (Poreh, 1995). Spronken-Smith and Oke (1999) have used small-scale physical modeling and reported that the sky view factor and thermal admittance are the main properties for developing the Park Cool Island.

3 Mitigation of urban heat island

3.1 Potential mitigating measures

Many studies have reported widely and successfully applied measures on mitigating the urban heat island effects with promising financial and environmental benefits. The possible mitigating measures could broadly be categorized as: (1) related to reducing anthropogenic heat release (e.g. switch off air conditioners); (2) related to better roof design (e.g. Green roofs, roof spray cooling, reflective roofs etc.); (3) other design factors (e.g. Humidification, increased albedo, photovoltaic canopies etc.).

Table 3 shows the major mitigating measures adopted or proposed by various researchers, which could also be categorized as those could only be implemented during the design and planning stage (e.g. sky view factor and building material etc.) and those could also be implemented after the design and planning stages (e.g. green areas and roof spray cooling). It seems that the planting and vegetation is the most widely applied mitigation measure which could achieve huge energy savings through temperature reduction of the area (Kikegawa *et al*., 2006; Ashie *et al*., 1999). It was reported in a study conducted by Spronken-Smith *et al*. (2000) that parks could help control temperatures through an evaporation of more than 300% as compared to its surrounding. The mitigating measures, however, are not limited to planting and vegetation only and have covered other design aspects with diversifying benefits. An example is the study conducted by Kolokotroni *et al*. (2006) who estimated that an optimized office building in an urban area could reduce 10% cooling energy demand through proper ventilation. Urano *et al*. (1999) reported that anthropogenic heat release has greater potential for modifying the day time thermal environment and wider buildings are better than small tall pencil buildings. Taha *et al*. (1999) have reported that proper values of surface-albedo could achieve temperature reductions and peak electric energy savings. Huang *et al*. (2005) have reported the effects of urban thermal environment on the

Table 3 Proposed mitigating measures, maximum temperature reduction and possible energy savings

Mitigation measure	Max. temp. reduction (°C)	Reported savings	Reference
Vegetation, lighter color of paving and cooler roofs	3.0	–	Rosenfield *et al*., 1998
Planting and vegetation	1.6	–	Tong *et al*., 2005
Planting and vegetation	1.5	–	Ca *et al*., 1998
Reducing anthropogenic heat and planting vegetation	1.2	40%	Kikegawa *et al*., 2006
Planting and vegetation	1.3	25%	Ashie *et al*., 1999
Planting and vegetation	–	10%	Yu and Hien, 2006
Proper ventilation	–	10%	Kolokotroni *et al*., 2006
Vegetation and suitable albedo	2.0	10%	Taha *et al*., 1999
Off air-conditions	1.0	6%	Kikegawa *et al*., 2003
Planting and vegetation	–	–	Spronken-Smith *et al*., 2000
Reducing anthropogenic heat and energy consumption, improvement in building design	–	–	Urano *et al*., 1999
Roof spray cooling	13–17 (ceiling temperature)	40% electrical consumption	Jain and Rao, 1974
Flow of water over roof	–	–	Sodha *et al*., 1980
Roof pond, roof spray cooling and moving water over roof	–	–	Tiwari *et al*., 1982
Shades, Highly reflective materials, Open and airy spaces, reduce heat release from buildings etc.	–	–	Yamamoto, 2006
Green and highly reflective roofs	–	–	Takebayashi and Moriyama, 2007
Humidification and albedo increase	–	–	Ihara *et al*., 2008
Photovoltaic canopies	–	–	Golden *et al*., 2007

–: Information not available.

comfort level of pedestrians while Rosenfeld *et al*. (1998) have reported ozone formation reduction of 12%.

3.2 Potential savings and practicability

Although literature covers a wide range of different mitigation measures with huge financial and environmental benefits, most of the proposed measures were based on numerical simulations and were not implemented. An example is the study conducted by Kikegawa *et al*. (2006) who have carried out computer simulation to report that the reduction of anthropogenic heat and planting vegetation on the side walls of buildings could reduce air temperature up to 1.2°C and reduce space cooling energy demand up to 40%. Ashie *et al*. (1999) have also used computer modeling and reported air temperature reduction of 0.4 to 1.3°C with building cooling energy savings of as much as 25% through planting vegetation. Yu and Hien (2006) have used computer simulation to report that parks and green areas could achieve 10% reduction of cooling load. Experimental studies were also conducted such as the field investigation carried out by Ca *et al*. (1998) who reported that planting a 0.6 km^2 park could reduce temperatures by 1.5°C and achieve potential savings of 4000 kWh in an hour of a summer day. Some of the suggested measures could not be implemented anyway, though, could possibly provide an idea or fruit for thought. An example is the study conducted by Kikegawa *et al*. (2003) who reported that temperature reduction of 1°C and cooling energy savings of 6% were possible in the case of all air-conditioners switched off. Another study conducted by Tong *et al*. (2005) reported that temperature reduction of 1.6°C was possible in the case of replacing urban developments by grass and shrub land. It could be seen that significant benefits have been reported by applying mitigating measures in many different areas. Also, almost all efforts were directed towards changing the controllable design factors but most of them were not implemented practically.

4 Discussion

It was noted that the generation of UHI is the environmental warmth due to the heat generated by the specific urban conditions. The various factors involved in the formation of UHI can be categorized as controllable and un-controllable. The controllable factors are mostly design and planning related which could be humanly controlled to some extent while the uncontrollable factors are environment and nature related which are beyond our control. The heat generated by anthropogenic heat sources and solar radiations were identified as the main sources of heat in an area. The former sources heat up the environment instantly and directly while a part of the heat generated by solar radiation heat up the environment directly and the rest are consumed by the urban structures which in turn heat up the environment indirectly. However, as the direct solar heating (DSH) will affect both urban and rural areas simultaneously and equally, the anthropogenic heat and the indirect solar heating (ISH) are the main causes of UHI. Of the two, the generation and reduction of UHI due to anthropogenic heat is straightforward while that due to ISH is more complicated. However, in view that most of the benefits of mitigating UHI were reported by reducing the ISH, this part is more important. The heat generated by anthropogenic heat sources depends on the energy use pattern and would have separate diurnal and seasonal cycles. The ISH, on the other hand, depends on the solar radiation, design of the settlements and the properties of materials and will also have varying diurnal and seasonal cycles. The UHII represents the temperature difference created by the cyclic heat generation of these main sources in urban and rural areas. Although the different diurnal and seasonal cyclic patterns of UHII shows that it follows the heat generated by these sources, the UHII is also influenced by many other factors. From the fact that UHI depends on the factors such as the wind velocity, cloud cover, the previous day UHII (Kim and Baik, 2002) week and weekend days (Kim and Baik, 2005; Simmonds and Keay, 1997) the mean UHII might better represent the two main sources.

The SEB and its components are determined to elucidate the heat generated and contained within the urban area and could be useful for selecting the proper mitigating measures. However, determining the SEB and evaluating some of its components correctly could be labors and tedious. It is reported that it is almost impossible to measure storage heat flux in an urban area; measuring anthropogenic heat may also require intense field survey. In almost all studies latent heat flux, sensible heat flux or storage heat flux were reported as the main heat inputs, and although anthropogenic heat could contribute as sensible heat, with the fact that all latent heat flux, sensible heat flux, or storage heat flux, have closely followed Q* (Arnfield and Grimmond, 1998; Christen and Vogt, 2004; Offerle *et al.*, 2006), the main reason of heat inputs remains the design and planning parameters.

The satellite technology and numerical simulation appeared to be widely applied supporting techniques in studying the UHI. The computer technique could especially be useful in determining the SEB and has been widely applied for determining the benefits of mitigating measures. However, as being pointed out, computer simulation needs strong validations. The proposed mitigating measures could be divided into three types, those which could not be implemented in anyway, those which have shown significant benefits but have not implemented and those which have been implemented either through simulation or through field survey. In comparison to the former two the last type might be more promising, however, it still lack practical implementation. The possibility is that practical implementation may not yield the reported huge savings and benefits. The best scenario could be the one where the possible temperature reduction due to the implementation of mitigating measures could be evaluated. In view that most of the promising benefits of mitigating measures have been reported for the controllable part of ISH i.e., the design and planning parameters, there is a need to quantify the significance of design and planning parameters. One possibility is that the UHII, the results of the components of SEB and the design and planning parameters of different areas are compared. The chance is that the areas in the same region would not have huge differences of design and planning parameters and it will be possible to quantify the significance. Once the possible temperature reduction due to a change in design and planning factor has been agreed upon, the UHI effects could be got rid of through suitable mitigating measures.

5 Conclusions

This study has been carried out to summarize and review the basic concepts, latest research methods, methodologies and tools used for understanding the generation, determination and mitigation of UHI. The various factors and their importance in generating the UHI has been discussed and described. The advantages and disadvantages, together with the possible areas of applications of different methods and tools available for determination and mitigation of UHI were also covered. It was concluded that the UHI is mainly caused by the Indirect Solar Heating (ISH) and anthropogenic heat. The controllable part of ISH, which covers the design and planning parameters, is complex but important and needs more research and efforts for achieving promising mitigation benefits. It was also concluded that there is a need to develop methods for ascertaining the UHI reduction with a change in the design and planning parameters.

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