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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:

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

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:

$$Q^* = Q_H + Q_E + Q_G \tag{2}$$

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 is necessary to first predict the actual UHI (atmospheric UHI) from the surface, by developing sensor-view models. Even though various sensor-view models have been adapted [24], a considerable gap still exists between the estimated and the actual ambient air temperatures: in addition to cosmic noises, large distance between urban surface and satellite affect on the performance of these sensors. It is necessary hence to develop a reliable filtration and conversion model between the radiation received by satellite sensors and the actual surface temperatures [75].

Another limitation of this approaches is that a significant portion of urban surfaces cannot be viewed due to the three-dimensional structures of the urban space. This means that the vertical field of the study domain cannot be captured in this scheme. Therefore, the UHI distribution has once again to be extracted from thermal data observed from a bird-eye point of view, using sensor-view models. The performance of current models has to be improved in order to correlate temperature of unseen vertical surfaces with the satellite-view. Improvement in spectral and spatial satellite sensors is also expected to provide more details information about the urban surfaces at lower cost and higher resolution. Similar to field measurement, thermal remote sensing can also be used to provide boundary condition for other UHI models [22,28,29].

2.2.3. *Small-scale modeling*

In this approach, the urban area is mostly replaced with prototype on obeying the similarity theory between real case and small-scale model [11]. The prototypes are tested either using wind tunnels [74] or outdoor spaces [21,27]. It is hard and sometimes unfeasible to ensure similarity between the real case and the prototype in outdoor spaces. For example, implementing solar radiation similarity is complicated in wind-tunnel modeling, while radiation is evidently one of the most significant factors in the UHI formation. Small-scale modeling is mostly used in UHI studies to verify, calibrate and improve the mathematical models (e.g. turbulence, stratification). However, similarity between model and prototype is the necessary condition for achieving accurate results.

Small-scale modeling can help to study the impact of limited number of parameters of a building on its environment (e.g. dimension, pollution dispersion) or over the small region of a city [12,56]. Although it is not easy to model complex dynamics of atmosphere interactions in this approach, this can be compensated by selecting appropriate boundary conditions [11]. Accuracy of a small-scale model in the problem depends on the ability to identify the most significant dimensionless numbers, to reduce the number of unmatched dimensionless numbers, and to develop criteria that reduce their impact [56].

The main drawback of small-scale modeling is mostly related to its cost. Also, it is very challenging to experimentally generate thermal stratification, in order to investigate the impact of stratification on flow patterns and on pollution concentration [74]. Furthermore, a complete adjustment is required to obtain similarity between boundary conditions of a small-scale experiment and a real problem (e.g. producing inflow, geostrophic or free-surface boundary condition in wind tunnel). Finally, as stated previously, this is a very time-consuming approach, thus only parts of an urban area can be simulated. Therefore, temporal and spatial investigation of the UHI under alteration of various parameters cannot be handled by this technique.

2.3. *Simulation approaches*

Beside the observation approaches, mathematical models have been developed to solve urban climate problems including UHI. However, due to the complexity of UHI, major simplifications are generally required. Nevertheless, computational techniques have advanced extensively over the past two decades and this allowed the researchers to solve mathematical models for large-scale problems. Among these models, energy balance and dynamical numerical approaches showed the most reliable and satisfactory outcomes.

2.3.1. *Energy balance model (simplified model)*

The energy balance budget for a building canyon was first suggested by Oke [50], (see equation (1)). This method uses the law of conservation energy for a given control volume, and considers the atmospheric phenomena, turbulence fluctuations and velocity field as heat fluxes. These fluxes are generally defined by analytical or empirical equations.

The urban canopy model (UCM) is derived from the energy balance equation for a control volume which contains two adjacent buildings. The model considers the energy exchanges with surfaces and ambient air in the urban canopy. The UCM predicts the ambient temperature and surfaces temperatures of buildings, pavements, and streets. However, the airflow is decoupled from the temperature field, and has to be defined as a particular input into the control volume. Logarithmic-law and power-law are widely assumed in the UCMs.

In the UCM approach, all surfaces and control volumes are connected to each other like electrical nodes. Equation (1) is then applied to each node, and the matrix of temperature and humidity of the surfaces are formed. By solving these matrices, the temperature and relative humidity of the domain are attained. Single layer [34] and multi layer [32] schemes are related to the number of nodes on the buildings' walls. Models can be also developed in one, two, or three dimensions. This approach is generally very quick as it only approximates building canopies with limited nodes. It provides also acceptable accuracy for large-scale energy consumption studies.

Absence of air velocity field serves as the major weakness of the energy balance models; the velocity field information is necessary in order to study the effect of flow pattern (e.g. eddy circulation, wake region and turbulence), to study formation of the atmospheric phenomena (e.g. precipitation and stratification), and to determine the sensible and latent heat fluxes. The assumption of these fluxes therefore with empirical correlations does not appropriately represent the interaction between velocity and temperature fields. Modeling transient effect is also an inherent challenging issue using this approach, since different uncoupled terms contribute to equation (1) varying in different time-steps. For example, thermal storage of building canopy materials may have large time step as compared with heat fluxes. Therefore to ensure reliable results, it is either necessary to select very small time-steps which increases the calculation time but neutralizes the major advantage of using this approach, or to clarify all terms based on one specific term (e.g. radiation) which physically weakens the modeling.

Providing database for three-dimensional geometry of building canopies and urban structures in a city is very expensive in terms of time and computer load. Therefore, the city is usually replaced with homogeneous columns of similar buildings [10]. The geometry and complexity of buildings are also approximated with limited grids on ground, roof, and walls. Apparently, this makes the spatial resolution of the energy conservation technique very weak, especially when it is required to study the thermal comfort at the pedestrian level.

2.3.2. *Computational fluid dynamics (CFD)*

Unlike the energy balance models in which velocity and temperature fields are separated, CFD simultaneously solves all the governing equations of fluid inside the urban areas; conservation of mass, potential temperature, momentum, and species (water vapor and chemical reaction). As a result, CFD is capable of obtaining more accurate information about UHI distribution within and above the building canopies than UCM. Consideration of complex details in addition to complicated atmospheric interactions of a city nonetheless is computationally and theoretically a challenging problem. The computational problem is due to the number of the control volumes or required nodes to simulate a city. On the other hand, theoretical problem is related to the unmatched temporal and spatial resolution of the phenomena which occur inside a city. For example, atmospheric and canopy-scale turbulence cannot be modeled in a same scale of time and length. Therefore, CFD simulations are mostly separated into different scales. This means that the simplification of Navier–-Stokes is significantly different due to the scale of the study. Two scales are generally used in UHI literature: meso-scale and micro-scale (urban-scale).

2.3.3. Meso-scale model

Meso-scale models are smaller than synoptic-scale and larger than micro-scale systems. The horizontal resolution of these models is approximately ranged from one to several-hundreds of kilometers. Also, these models vertically vary with depth of Planetary Boundary Layer (PBL) between 200 m and 2 km. This layer exists between the earth surface and geostrophic wind. In meso-scale models, large-scale interactions under the PBL are resolved, including atmospheric stratification and surface layer treatment. In this approach, the Navier–Stokes equations are either based on hydrostatic or non-hydrostatic hypothesis to include the atmospheric stratification effect. In hydrostatic models, the equation of motion in the vertical direction is simplified into a balanced equation between the buoyancy and the pressure terms. On the other hand, in non-hydrostatic models the equation of motion in the vertical direction is expressed with full Navier–Stokes equation.

Meteorological schemes mostly use Monin–Obukhov or other similarity scheme to model surface sub-layer [4,79]. Meaning that building canopies are assumed to be like aerodynamic roughness. This implies that in meso-scale models the whole urban canopy layer with its complex details is replaced with a roughness number. Thus, information about the quantities within the canopy layer is not available. This simplification helps to understand the processes occurring within the urban surface layer and above the canopy layer (i.e. surface drag, shearing stress, wind profile forms and turbulence). The accuracy of a meso-scale model prediction strongly depends on database provided for the Land-Use Land-Cover (LULC). Detailed information of micro-scale surfaces (e.g. thermal properties, geometry, radiative characteristics) is rarely available for the entire urban region, and even if it is, applying these details to meso-scale model is very CPU-intensive. Since the spatial resolution is in magnitude of a few kilometers, it is also necessary to assume a meso-scale zone as a homogeneous area, and estimate the surface properties with bulk values (e.g. albedo, emissivity, roughness).

Appropriate assumption of the PBL is another important issue in meso-scale methods. The PBL is directly influenced by its contact with a planetary surface. Therefore, in this layer, many physical phenomena are taking place which influence velocity, temperature, moisture, turbulence fields. For example, when the positive buoyancy of the surface created by solar radiation or moisture condensation is strong, the PBL generates strong turbulence and produces positive buoyancy under thermal instability. It is also feasible that negative buoyancy opposes the turbulence and weakens considerably the vertical mixing. This phenomenon happens typically when the earth's surface is colder than the prevailing air. Although many PBL models have been proposed [18], the equations are considerably non-linear and influenced by properties of the land's surface and the free atmosphere's interactions. Therefore, further improvements are required in this subject area. In addition, many moisture schemes [58,65,71] and soil models [14,78] have been developed for integration with PBL models. The interaction between cumulus and radiation is also required for meso-scale modeling. It is noteworthy to mention that cumulus, soil, radiation and PBL models are coupled in meso-scale models and development of these interactions therefore is a wide topic of research. For example, the cumulus model provides information for calculation of radiation energy absorbed by urban surfaces. Afterwards, PBL model estimates the air moisture, temperature and velocity using this energy. Again, these obtained data are simultaneously used by radiation model to estimate upward long and short-wave radiation. Furthermore, the accuracy of meso-scale models is a function of proper wind and surface temperature boundary condition that is generally provided by observational techniques [61,73].

2.3.4. Micro-scale model

Unlike the meso-scale model, micro-scale CFD resolve the conservation equation inside the surface layer. Meaning that the horizontal spatial quantities are assumed with bulk values in meso-scale model, where those are simulated with actual geometry and details with surface layer interactions in micro-scale model. These interactions are generally assumed with Monin–Obukhov similarity inside the PBL in meso-scale models. However, it is not feasible to apply the micro-scale models for an entire city, with all the details and geometries, due to the high computational cost. Therefore, the simulations are horizontally limited to a small domain in magnitude of some blocks of buildings (few hundreds of meter). On the other hand, the treatment of the PBL in micro-scale model is not as comprehensive as meso-scale model. It implies that micro-scale model mostly does not include the atmospheric interactions like atmospheric vertical mixing or Coriolis effect. Generally, it can be concluded that the micro-scale model is an appropriate approach to study the high-Rossby number problems.

Observational schemes can significantly improve the mentioned limitations of boundary conditions [42]. However, providing boundary conditions for the micro-scale is even more complicated than meso-scale models. In this model more measurements is necessary due to high fluctuation of quantities at the surface layer. Although assumptions (e.g. log-law, power-law, and outflow) are usually made for the boundary conditions, these approximations are physically weak due to stochastic nature of flow velocity, and different buildings' height and geometry.

Similar to the meso-scale model, the treatment of turbulent closure and radiation significantly affect on accuracy of the micro-scale model prediction.

2.3.5. Turbulence treatment

Many theories have been proposed to model the turbulence such as Direct Navier–Stokes (DNS), Large Eddy Simulation (LES), and Reynolds Average Navier–Stokes (RANS). Although better accuracy can be achieved using LES and DNS [41], the application of these schemes is computationally very expensive. Instead, RANS (e.g. k–ε and $k - l$) is widely used for turbulent modeling in UHI studies due to its lower computational cost [31,77]. However, this scheme does not physically show good performance in simulation of the building canopies, especially inside the wake region [72]. This implies that accurate modeling of turbulence phenomena is still one of the weakest points of the CFD simulation. In addition, the scale of study significantly affects the development of RANS. This is related to the turbulence length-scale which describes the size of the large energy-containing eddies in a turbulent flow. Different types of k–ϵ models have been used as reliable schemes in canopy-scale simulation [37,46]. In the development of the meso-scale turbulence model, the effect of buoyancy mostly created by urban surface layer is as significant as viscous turbulence. In recent years, various one and two-equation turbulent schemes, standard $k-1$ and k–ε, and hybrid k–$\varepsilon - 1$ models have been proposed [19,76,79].

3. Modeling parameterization

3.1. Latent and sensible heat treatment

The latent and sensible heat transfer between airflow and surfaces has to be determined in CFD or UCM approaches. In the micro-scale model, the surface fluxes is obtained by solving the velocity and moisture equations, either using fine meshes near the wall or by using the wall-function method [35]. The wall-function assumption shows good performance in micro-scale UHI studies, especially when the flow is not in low-Reynolds numbers [72]. In the meso-scale model, however, rough aerodynamic condition is assumed for the surface layer, and the effect of velocity and moisture transfer is usually predicted by Monin–Obukhov similarity [38,39].

As stated before, the velocity field is an external assumption in UCM and the empirical formulations therefore are mainly used to calculate sensible heat fluxes. For example, Jurges [26] proposed the following equation for a case in which surface temperature is higher than air temperature:

$$Q_{\mathrm{H}} = \alpha(T_S - T_a), \quad \alpha = \begin{cases} 6.15 + 4.18U_a & U_a \le 5\ \mathrm{m/s} \\ 7.51U_a^{0.78} & U_a > 5\ \mathrm{m/s} \end{cases} \tag{3}$$

where T_{S} and T_{a} are the surface and air temperature, respectively, and U_{a} is the wind velocity at reference height, Z_a. When $T_{\mathrm{S}} < T_{\mathrm{a}}$, equation (3) may overestimate the flux under stable weather conditions, the Monin–Obukhov theory is suggested to include the effect of stability [34]:

$$Q_{\mathrm{H}} = \rho c_p u_* T_* \tag{4}$$

where c_{p} is the specific heat, ρ is the air density, u^* is the friction velocity and T^* is the temperature scale. u^* and T^* are obtainable from the following logarithmic equations:

$$U_a = \frac{u_*}{k}\left[\ln\left(\frac{z+z_0}{z_0}\right) - \Psi_m\right]$$

$$\Theta(z) - \Theta_G = \frac{\mathrm{Pr}}{k}T_*\left[\ln\left(\frac{z+z_{0t}}{z_{0t}}\right) + \ln\left(\frac{z_0}{z_{0t}}\right) - \Psi_t\right] \tag{5}$$

where Θ is potential temperature, z is the vertical direction, z_0 and z_{0t} are the zero-plane displacement for wind and temperature, k is the von karman constant, Pr is the turbulence Prandtl number, and ψ_{m} and ψ_{t} are respectively the integrated velocity and thermal universal function for atmospheric stability which has different values under stable and unstable weather condition, and zero value under neutral condition. It is worth mentioning that Monin–Obukhov formulation requires a complete database for surfaces. It is not also correct to physically find u^* for a certain surface by using U_{a} instead of flowing velocity on that surface. Meaning that U_{a} is the reference velocity and may have completely different pattern from surface velocity.

Kanda [27] and Masson [39] used the following equation to obtain sensible heat transfer between canyon faces (including top-canopy) and atmosphere:

$$Q_{\mathrm{H}} = \rho c_p C_{\mathrm{H}} U_a (T_S - T_a) \tag{6}$$

where T_{a} is the air temperature at a reference height Z_{a}, C_{H} is the local bulk transfer coefficient between each face of the canopy and the reference height. In this model, defining C_{H} is very difficult, since it is a function of surface and flow regime. One way to find C_{H} is to use empirical formulation using in-situ or wind-tunnel measurement, although the result is not general and changes from case to case. The following equation is proposed by Ref. [16]:

$$C_{\mathrm{H}} U_a = \left(11.8 + 4.2\sqrt{U^2 + W^2}\right)^{-1} \tag{7}$$

where U and W are the prevailing wind velocity components over the canopy.

The treatment of latent heat flux is very similar to the framework of sensible heat flux. For example, it is possible to use the Monin–Obukhov similarity to obtain Q_{E}, similar to equation (4) [34,44]. Similar analogy with equation (6), the following equation is used by Ref. [27]:

$$Q_E = l\rho B C_{\mathrm{H}} U_a (q_s - q_a) \tag{8}$$

where l is the latent heat of vaporization, B is the wetness parameter for each canopy surface ranged from 0 (completely dry) to 1 (completely wet) depending on the vegetation or the water availability at that surface, q_{a} is the specific humidity at the reference height z_{a}, and q_{s} is the saturated specific humidity for the surface temperature. Similar analogy with equation (8) is also used for the empirical form of latent heat flux [39]:

$$Q_E = l\rho\delta C_{\mathrm{H}} (q_s - q_a) \tag{9}$$

where δ is a fraction of each surface in the building canopy (δ(top-canyon) = 1).

3.2. Heat storage effect

Heat storage fluxes within the urban areas contribute in formation of UHI. Part of this heat is generally conducted through the soil, pavements, roof and buildings' material and part is stored within the soil and ambient air of the building canopies. In the solid domains, the storage flux can be determined using equation (1) which takes into account radiation, anthropogenic heat release, sensible and latent heat fluxes in surfaces, including ground, roof, and walls. Using heat-diffusion equation, temperature distribution inside surfaces can be obtained using both urban canopy models and dynamical numerical models:

$$\rho c_p \frac{\partial T}{\partial t} = Q_{\mathrm{Gen}} + \nabla\cdot(k\nabla T) \tag{10}$$

where ρ is the soil density, c_{p} is the heat capacity of surface, k is the thermal conductivity, and Q_{Gen} is the heat source or sink. Usually, the sink or source term is omitted, and materials are assumed homogeneous [27]. The equation can also be used in the form of one, two, or three dimensions. Moreover, advanced multi-layer soil models are generally adapted to predict transpiration and moisture. Treatment of the heat storage effect on air volume of the study domain is different in UCM and CFD. In CFD simulation, when Navier–Stokes equations are solved considering a transient case, this effect is automatically taken into the account. On the other hand, different schemes are proposed to include the heat storage effect in UCM. Oke [49] proposed simple regression relationships between ΔQ_{S} and Q^* for different surface types. Furthermore, Nunez and Oke [48] parameterized Q^*, Q_{G} and, Q_{H} based on empirical data. Oke and Cleugh [52] showed a relation – a hysteresis loop – between the heat storage and the net radiation. The Objective Hysteresis Model (OHM) of Grimmond et al. [23] made use of this concept:

$$\Delta Q_s = a_1 Q^* + a_2 \left(\partial Q^* / \partial t \right) + a_3 \tag{11}$$

where a_1, a_2, and a_3 are function of the surface type. OHM concept is later applied in meso-scale models [69] and UCM [10].

3.3. Anthropogenic heat release

The state of knowledge on anthropogenic heat flux, known as Q_F in equation (1), is well summarized by Oke [51]. Incorporation of anthropogenic heat flux in simulation models of urban climate is relatively straightforward, involving the addition of a source/sink term, usually constant, in the surface and control volume energy budget equations. For example, anthropogenic heat can be expressed by the following formulation [23]:

$$Q_F = Q_{FV} + Q_{FH} + Q_{FM} \tag{12}$$

where Q_{FV}, Q_{FH}, and Q_{FM} are the heat released by vehicles, stationary sources, and metabolism, respectively.

3.4. Radiation model

The influence of radiation fluxes on the formation of UHI is very significant and many models have been developed to define the radiation exchange mechanism inside urban areas. However, many limitations make radiation almost the weakest point of UHI studies. The radiative transfer equation (RTE) for an absorbing, emitting, and scattering medium was presented by Chandrasekhar [13]. However, using this equation is CPU-intensive in urban studies. Therefore, surface-to-surface schemes are more popular in this field. In this method, the effect of air as medium on scattering is usually neglected, while many studies show that scattering caused by pollution and particulates is a significant factor in changing both downward and upward radiations [50].

A surface-to-surface radiation model, equation (13), is an appropriate technique for modeling the enclosure radiative transfer without participating media. The net radiation budget to surfaces within a city is mostly simplified as follows:

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow \tag{13}$$

where K and L represent short and long-wave radiation, respectively, and $\downarrow\uparrow$ are for downward and upward radiation. One of the main problems in radiation models is to determine the interaction of surfaces to each other and sky. Therefore, the radiative transfer equation cannot be properly developed in control volume of a city. For example, it is not easy to trace the absorption ratio of diffuse part of solar radiation in surfaces.

Radiation models mostly use diffuse assumption for surfaces [32,38,39]. This implies that the reflection of incident radiation at one surface is isotropic with respect to a solid angle. Also, radiation models are typically solved using the gray material assumption, since the modeling of non-gray radiation is still under development [20].

Moreover, cumulus and cloud cover models are extremely significant in order to find the fraction of the incident solar radiation as well as long-wave exchanges between sky and urban surfaces. These models are mostly coupled with atmospheric models (i.e. PBL and moisture schemes) in meso-scale. However, the cumulus and cloud cover models are typically neglected in the UCM and micro-scale models due to the lack of atmospheric interactions in these schemes.

3.4.1. Short-wave radiation

Solar radiation contributes significantly to diurnal heat island when the sky is mostly clear and calm. Solar radiation is partly absorbed by urban surfaces, and partly reflected. The incident solar radiation on surfaces is also composed of direct and diffuse fractions. Assessment of the direct and diffuse portions is a function of cloud cover which is not physically easy to find. Many atmospheric models have been developed to evaluate the cloud cover [17,66].

Another important issue in short-wave radiation models is how to trace the reflected portion of direct and diffuse parts of solar radiation, which is extremely CPU-intensive. This means that only limited reflections have to be simulated [32,34]. The main problem of radiation models is the calculation of the sky-view factor for each surface in addition to the view factor between a surface and other surfaces. The calculation of the view factor for all surfaces inside urban canopies is also very CPU-intensive and impractical.

3.4.2. Long-wave radiation

Long-wave radiation is more dominant in the formation of nocturnal UHI. In this case, warmer surfaces of the city cannot properly emit energy to the sky. This is due to the presence of cloud or low-view factor of the sky seen by buildings. Therefore, it is necessary to develop a model that traces the long-wave radiation from each surface to the sky and other surfaces [15,38]. In addition to the high CPU-cost of the tracing model, a complete database of urban surface properties (i.e. emissivity, direct albedo, diffuse albedo, sky-view factor and other surface view factors) is also required for calculation of the long-wave radiation inside the building canopies.

3.5. Effect of trees and ponds

Trees significantly affect the environment energy balance by transpiration from leaves, by shading of the solar radiation and by blocking the wind. This implies that the effect of trees is as important as buildings in the urban study literature. The transpiration effect of trees is mostly included within UCM and CFD by adding tree-canopy models [43] or by considering a source term in latent energy balance of the surfaces [38]. Also, the shading effect is mostly presented in radiation models. In UCM, the blocking effect of trees is generally considered in drag equations [39]. On the other hand, the trees are mostly replaced with simple shapes to show the obstacle effect in CFD, since the complicated geometry of trees is extremely difficult to simulate [36].

Similar to trees, water ponds changes the energy budget of building canopies' control volume. Comparing to solid materials, these elements have different physical and thermal properties. Therefore, they can store the heat inside or release the latent heat flux through the city canopies [34,39]. The pond effect is mostly assumed with moisture effect in CFD and UCM [5]. However, it is necessary to develop a comprehensive pond model considering physical and chemical interactions.

3.6. Boundary condition

The use of observational schemes is the most reliable method to provide boundary conditions for UHI studies. As stated before, assumptions are generally made in the UHI study literature for inflow, outflow, ground, soil, building surfaces, top-canopy, and lateral boundary conditions, since it is not spatially and temporally possible to always have observational data. It is noteworthy that even if these approximations are widely used in UHI literature, mathematical approaches should be adapted to better express the interaction of multi-scale models with each other. Development of more accurate wall boundary conditions to clarify the interaction of solid and fluid boundaries is still a challenging problem.

3.6.1. Inflow boundary condition

Wind flow, temperature, and humidity profiles over the city terrain are affected by surface layer roughness. These profiles over urban canopies are inside the surface layer of the PBL. A semi-empirical approach, the log-profile, is generally used to describe the vertical profile of horizontal distribution above the ground within the atmospheric surface layer [70]. This layer is a function of weather stability, and is approximately limited to 10 percent of the PBL. The log-profile is similar to equation (5). Zero-plane displacement varies significantly as a result of flow obstacles like trees or buildings. However, the height is generally approximated as 2/3 of the average height of the obstacles [39]. For temperature and humidity profiles, the equation is almost the same as that of velocity [44]. When weather stability is under neutral condition, or the roughness information is not available, the inflow profile, as a simple and reliable option, is assumed with power-law:

$$U_z = U_a\left(\frac{z}{z_a}\right)^{\alpha} \tag{14}$$

where U_a is defined the reference wind speed at reference height z_a, and α is the power-law exponent.

3.6.2. *Outflow boundary condition*

Outflow condition is typically assumed as zero gradient condition in UHI studies [77]. It has been proven that this could be a reasonable assumption, if the distance from building roughness (tail length) is appropriate for fluid to reach the fully-develop condition [72].

3.6.3. *Ground and soil boundary conditions*

To provide ground boundary condition of temperature and humidity for building or urban-scale problems, it is necessary to include conduction heat transfer through the surfaces. Also, treatment of humidity is generally demonstrated by adding source term to species equation in CFD and equation (1) in UCM [10]. In meso-scale models, the Monin–Obukhov similarity is generally assigned to the ground boundary condition of velocity.

3.6.4. *Building surface boundary condition*

For building surfaces, wind velocity is usually assumed to follow logarithmic-law (wall-function) for smooth wall [77]. On the other hand, studies have been carried out using roughness for building surfaces [72]. If wall thickness and air conditioning details of the building is known, it is also possible to assume the indoor air condition (e.g. SET*) as boundary condition. It is also feasible to integrate the calculation with a building energy calculation code (e.g. DOE2, TRANSYS) to improve the accuracy of simulations [42] using temperature distribution within the building instead of only one SET* temperature.

3.6.5. *Top-canopy and lateral boundary conditions*

The integration of the surface layer with the atmospheric layer is an important parameter in selecting the suitable boundary conditions for top-canopy and lateral faces. Using observational data over some section of the cities serves as the best option [17]. However in the absence of the measurements, nesting scheme can be used to provide acceptable boundary condition through meso-scale models [45]. In this case, unknown variables of the model at the lateral boundaries for the small area are interpolated from the corresponding computed values of meso-scale models.

If the height of the computational domain is higher than the height of the atmospheric boundary layer above an urban area (approximately 1–2 km above the ground surface.), it can be concluded that geostrophic wind serves as a good approximation. Therefore, turbulence, mean potential temperature, and water vapor mixing ratio can be set equal to constant values. Also, the free-sleep condition can be used as top condition when the height of the domain is high enough to be assumed as a fully-developed situation [40]. In this case, Neumann boundary condition can be specified at the lateral boundaries. This indicates that there is no change in the physical variables of the horizontal directions at lateral boundaries.

4. Developed tools for UHI mitigation and prediction

4.1. *Simulation tools*

As pointed out the complexity and quantity of urban details, the theoretical weakness and the high cost of simulation

Table 1
Comparison of the urban heat island simulation approaches.

Approach	Urban Canopy Models	CFD	
		Meso-scale	Micro-scale
Governing Equation	• Energy balance equation (1) • An input assumption for velocity equation of the canopy layer • Heat conduction equation for surface	• Navier–stokes equations (Including Coriolis term with hydrostatic or non-hydrostatic assumption) • Monin–Obukhov for ground surface • Heat conduction equation for soil	• Navier–stokes equations • Monin–Obukhov for surfaces of the urban structures (e.g. wall, ground) • Heat conduction equation for surface
Major Limitations	1. Decoupled velocity field from temperature and moisture 2. Assumption of a city with similar homogeneous array of buildings 3. Limited resolution of urban geometry 4. Only good for steady state solution 5. Neglecting the atmospheric effect 6. Empirical assumption for convective latent and sensible heat	1. Assumption of the urban canopy layer as roughness 2. Difficult to provide Land-Use Land-Cover database 3. Accuracy dependent on field measurement 4. Modeling of the turbulence	1. Not including the atmospheric phenomena 2. Difficult to create database for canopy details 3. Providing boundary conditions 4. Modeling of the turbulence
Maximum Domain Size	City	City	Building Block
Spatial Resolution	1–10 m	1–10 km	1–10 m
Temporal Resolution	Hour	Minute	Second
CPU-Cost	Medium	Very high	Very high

Table 2
Comparison of tools developed for Urban Heat Island studies.

Name	Type	Dimension	Surface layer	Turbulence scheme
[6]	Energy Balance Model	1D-Single Layer	UCM	Drag Equation
UHSM – [10]	Energy Balance Model	1D-Single Layer	UCM	Drag Equation
RAUSSSM – [80]	Energy Balance Model	1D-Multi Layer	UCM	Drag Equation –0 Equation
[34]	Energy Balance Model	2D-Single Layer	UCM-Monin–Obukhov	Drag Equation
TEB – [39]	Energy Balance Model	2D-Single Layer	UCM-Monin–Obukhov	Drag Equation
[21]	Energy Balance Model	2D-Single Layer	UCM-Monin–Obukhov	Drag Equation
SUMM – [27]	Energy Balance Model	3D-Single Layer	UCM-Monin–Obukhov	Drag Equation
UCSS – [7]	CFD (Micro-scale)	3D	Monin–Obukhov	2 Equations k–ε
[38]	CFD (Meso-scale)	2D	Monin–Obukhov	2 Equations k – l
MM5 – [17]	CFD (Meso-scale)	3D	Monin–Obukhov	2 Equations k – l
RAMS – [54]	CFD (Meso-scale)	3D	Monin–Obukhov	2 Equations k – l – LES
[53]	Energy Balance Model – CFD (Meso-scale)	Single Layer – 3D	UCM	Drag Equation –0 Equation
AIST-CM-MM – [32]	Energy Balance Model – CFD (Meso-scale)	1D-Multi Layer	Monin–Obukhov	Drag Equation, –0 Equation
HOTMAC – [79]	Energy Balance Model – CFD (Meso-scale)	3D	UCM-Monin–Obukhov	2 Equations k – l, –Mellor-Yamada
WRF – [66]	Energy Balance Model – CFD (Meso-scale)	3D	UCM-Monin–Obukhov	2 Equations k – l

approaches, difficulties in providing high-resolution, continuous and real time boundary conditions, and the inconsistency of the observational method make the UHI investigation a challenging one.

Table 1 summarizes the developed UHI study models based on the governing equations, major limitations, domain size, spatial and temporal resolution and CPU-cost. It is obvious from Table 1 that meso-scale tools are practical approaches when underlying surface details are not important (e.g. urban-scale energy conservation and pollution dispersion). On the contrary, for cases with concern about canopy layer phenomena (e.g. pedestrian thermal comfort, building-scale energy conservation) micro-scale CFD and UCM are more useful schemes. Nonetheless, because of the high computer cost, real time and real-size simulation of a city is not possible and major assumptions have to be made.

Based on existing simulation models, as shown in Table 2, many tools have been developed to predict UHI and/or to investigate the effect of mitigation strategies. It is noteworthy that selection of the most appropriate models depends on objective of the application: decreasing urban temperature, improving the OAQ, reducing heat island related diseases, or energy conservation.

4.2. *Tools integration*

The integration of micro-scale and meso-scale models has been recently proposed [45]. The integrated model predicts large-scale phenomena and interactions above the surface layer using a meso-scale model. On the other hand, this model simultaneously obtains the required data from surface layer using micro-scale models. Inversely, it is possible to solve a micro-scale problem and at the same time obtain the required information at top-canopy level from a meso-scale approach. The integrated model also provides better boundary conditions by transferring data from larger scale to smaller one (nesting) or vice versa [64]. The integration therefore helps to cover a wide range of problems. For example, the new weather research and forecasting model (WRF) is developed to integrate a meso-scale model with a canopy-scale UCM [66]. This integration is not straightforward and there are number of issues to be overcome.

Unmatched temporal and spatial resolution of the scales are the main problem that may cause missing information through the data transfer between the scales [69]. Moreover, details might be lost where data averaging is performed from finer to coarser grids or vice versa. Furthermore, as discussed previously, since discretization of the domains varies in micro and meso scales, the continuity equation may not be satisfied at the interfaces.

4.3. *Urban heat island study prospective*

Buildings change the energy balance in urban areas and they are considered as the main cause of UHI formation. Thus, future buildings and corresponding HVAC systems have to be more focused on energy conservation and enhancing not only the indoor but also the outdoor air quality. The implemented tools, as shown in Table 2, are useful for prediction and mitigation of UHI.

The prediction of the UHI distribution is possible through the simulation of the current situation in an urban area [57,60]. As a result, it is possible to create a UHI map which helps to distinguish the vulnerable regions of a city [33,36]. Furthermore, peak and amount of the energy demand increase can be evaluated through this method [1,3].

On the other hand, UHI mitigation is feasible after studying the effect of countermeasures with the use of existing tools. Meaning that urban or building designers can simulate the impact of countermeasures before construction stage for the purpose of energy conservation [1,25,30] and pedestrian comfort enhancement [9,33].

5. Summary

This review presents observational and simulation methods that have been widely used to predict and mitigate the urban heat island phenomenon. Recently, due to extensive computer progress and limitations of observation methods, researchers focused more on simulation approaches such as UCM and CFD. However, currently developed tools have major limitations, including complexity and plethora of urban details, theoretical weaknesses of approaches, high computational cost of simulations, and shortcomings in providing high-resolution, continuous and real time boundary conditions. To enhance progress of applicable tools, model integration has been proposed in order to take advantage of multi-scale models. However, efforts must be made to make these models more compatible with each other. If so, these tools end up being extremely useful to advance urban planning, building design, and human outdoor comfort.

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