Sustainable Cities and Society 19 (2015) 200–206

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs

Engineering Advance

Recent challenges in modeling of urban heat island☆

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ARTICLE INFO

Article history:
Available online 29 May 2015

Keywords:
Urban heat island
Modeling
Review

ABSTRACT

The elevated air temperature of a city, urban heat island (UHI), increases the heat and pollution-related mortality, reduces the habitats' comfort and elevates the mean and peak energy demand of buildings. To countermeasure this unwanted phenomenon, a series of strategies and policies have been proposed and adapted to the cities. Various types of models are developed to evaluate the effectiveness of such strategies in addition to predict the UHI. This paper explains the compatibility of each type of model suitable for various objectives and scales of UHI studies. The recent studies, mainly from 2013 to 2015, are further categorized and summarized in accordance with their context of study.

Contents

☆ This is an Engineering Advance paper.

Abbreviations: UHI, urban heat island; PET, physiological equivalent temperature; ANN, artificial neural network; TEB, town energy budget; LST, land surface temperature; BEM, building energy model; UCM, urban canopy model; MCM, microclimate model; MM, meso-scale model; CFD, computational fluid dynamics; GIS, geographic information systems; Modis, moderate-resolution imaging spectroradiometer; LIDAR, laser illuminated detection and ranging.

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http://dx.doi.org/10.1016/j.scs.2015.04.001
2210-6707/

1. Introduction

There has been a drastic increase in the world population in recent years, new megacities are born and existing megacities become more populated (Fig. 1) [1]. Besides new economical, managerial and social challenges associated with growing cities, a deformed energy budget pulls them toward a warmer climatic condition, known as urban heat island (UHI). Highly populated areas mandate cities to develop either vertically or horizontally, resulting in more released anthropogenic heat, a higher blockage effect against urban ventilation, a higher absorption of solar radiation due to the implementation of artificial materials, and eventually a reduced long-wave emission to sky due to the blockage effect of buildings [2,3].

The elevated temperature triggers heat-related diseases and premature deaths in the cities [4,5]. Moreover, the elevated air and surface temperatures during UHI events increase the city-scale mean and peak cooling energy demand due to lower efficiency of HVAC systems in higher temperatures as well as a significant drop in the thermal comfort level [6]. Despite various efforts in mitigating the UHI effect, the effectiveness of the mitigation strategies cannot be evaluated with a high level of certainty due to weakness of current models in their design and prediction stages. This implies that the developed tools should precisely include a series of complex phenomena occurring in a city and avoid unrealistic assumptions as well as the intensive computational calculations.

This paper aims to summarize the recent efforts in modeling of the UHI effect. For this purpose, various studies in building, neighborhood and city scales are firstly identified. Then, these works are summarized in six major categorizes of research interest, including urban ventilation and surface material alteration, health and comfort, UHI spatial–temporal variation, model evaluation and enhancement, future temperature forecast, and building energy saving.

2. Modeling approaches – goal of the study

The goal of a UHI study delineates the type of an adapted model. Urban physics include a combination of complex and diverse phenomena, interacting in different scales from human body to city size. Therefore, it is very crucial as a first step of a UHI study to simplify physics and scale of the investigated subject. This implies that a suitable model can be only identified in compliance with the defined objective in order to minimize the complexities and computational costs of the study.

Mitigation strategies such as urban ventilation and surface material alteration [7,8], improvement of occupant and pedestrian comfort/health [9–11], and building energy demand [12•] are amongst widely investigated UHI topics. In general, the mentioned objectives are recognized to be in accordance with different perspectives from different communities including building scientists, architects, urban climatologist, meteorologists and geographers.

3. Scale of the study

The UHI models are diverse in terms of scale with respect to the aim of a study, changing from building-scale for investigation of the impact of the UHI on thermal comfort of a pedestrian to urban-scale for exploring the effect of synoptic wind on urban ventilation.

3.1. Building-scale models

These models, known as building energy models (BEM), are mainly limited to an isolated building envelope where the influence of neighboring buildings on its energy performance is neglected. This implies that BEMs are developed based on an energy balance applied to the building's control volume. Outdoor parameters such as temperature, solar radiation, long-wave radiation, and moisture are external inputs into such models. Various robust BEM tools (e.g. EnergyPlus, ESP-r, TRNSYS) are utilized to investigate the response of the building envelope against possible future scenario of climate change and exacerbated urban climate [13]. Obviously, these models are simplistic in representing the mutual impact of a building with its surrounding area and thus their integration with larger scale models is inevitable when the effect of UHI on building energy performance is investigated.

3.2. Micro-scale models

The interaction of a building with its surrounding environment in the surface layer is the basis of the development of microclimate models (MCM), which are widely employed by building scientists and architects. In principle, solar radiation and surface convection from the buildings' surfaces can be included in such models. In many MCMs, the airflow patterns around and within buildings are resolved using computational fluid dynamics (CFD) technique, dealing with the governing equations of the flow (Navier–Stokes equations). Another type of MCM, urban canopy model (UCM), has been broadly utilized to investigate the energy budget of an urban canopy layer [14]. Unlike CFD based MCMs, the airflow model is decoupled from the energy budget equations in UCMs. In general, the impact of different parameters such as building orientation, street canyon aspect ratio, surface materials, vegetation and tree

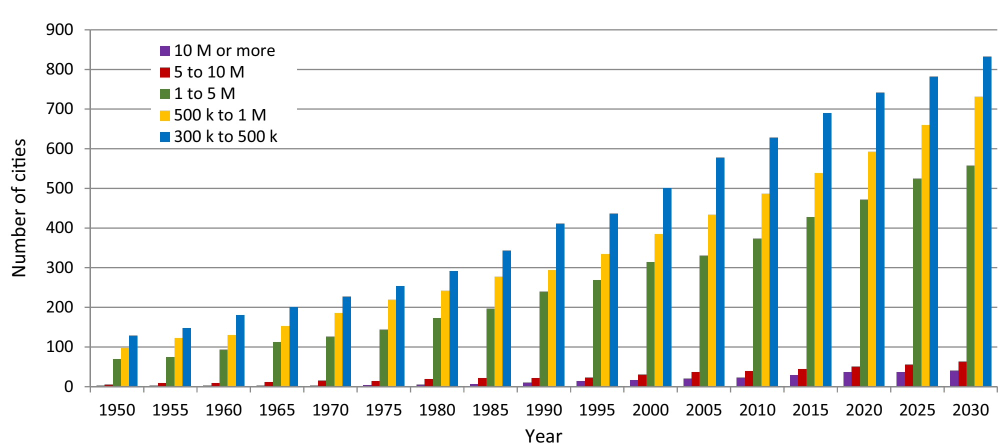

Fig. 1. The growth rate in number of cities with various populations during 1950–2030 [1].

planting on the calculation of surface convection, pedestrian comfort, and urban ventilation can be investigated using CFD and UCM MCMs [3,15,16].

The weakness of the microclimate CFD models is their limited domain size (few hundred meters) due to the extensive computational cost. UCMs are also weak in the detail presentation of airflow around the buildings for example in thermal comfort associated studies.

3.3. City-scale models

Investigation of the large-scale UHI variation of a city is broadly adopted in urban climatology and meteorology fields. The impact of urban-scale policies to mitigate the UHI, e.g. urban ventilation, pollution dispersion management, and greening, is mostly analyzed using meso-scale (MM) tools. The developed models are based on the governing equations of fluid dynamics whilst equally important models such as radiation, cloud cover and soil are integrated into the calculations. As the major limitation, the meso-scale models are applied on very coarse cells, implying a weak resolution on the surface layer to observe interactions between buildings and their environment.

City-scale observation and modeling of the UHI is one of the applications of the remote sensing. The thermal images taken by satellites (e.g. Terra and Aqua) and airborne measurement devices are processed to correlate surface temperatures and land-use/land-cover of a city. For this purpose, regression models are commonly developed to explain spatial–temporal land surface temperature (LST) variation associated with parameters such as topographic position, land-cover diversity, building volume per area, orientation, and anthropogenic heat release [17]. The regression models, however, have low spatial resolution. They are only valid for a specific location and barely can be extended to other regions. Moreover, the retrieved images such as moderate-resolution imaging spectroradiometer (MODIS) should be adjusted against surface emissivity and atmospheric effects (absorption and emission) before being used in the UHI studies [18]. As an improvement to the earlier UHI research on the basis of planar satellite imagery and geographic information systems (GIS), laser illuminated detection and ranging (LIDAR) technique is exploited to develop 3D model of the cities for further representation of the complex geometric structure of urban areas [19•].

4. Recent studies

Both deterministic and stochastic models are broadly developed to implement the mentioned UHI study aims. These models are mainly supported with large datasets obtained from local weather stations, mobile measurement stations, and satellite thermal imagery. Airflow (i.e. Meso and micro-scale CFD) and energy balanced (i.e. UCM and BEM) models applied in different scales are amongst deterministic approaches. In many scenarios, a multi-scale model combined with airflow and energy balanced models is developed to enhance the accuracy of the simulation. On the other hand, statistical models such as artificial neural network (ANN) and regression methods are widely implemented to correlate the complex and large scale characteristic of a city to the UHI.

Some of the UHI studies in the last two years are summarized in Table 1. The table is categorized based on the study themes as explained in the next section. The studies in each theme are further summarized based on their aims, case study locations, type of the developed models, and utilized observational techniques. As shown in Table 1, a series of studies addressed the development of models to investigate the impact of common UHI countermeasure such as urban ventilation and material alteration. A significant number of studies also focused on the observation and prediction of the spatial–temporal UHI variation.

4.1. Urban ventilation and surface material alteration

The shape of a building, the ratio of a street's height to its width, orientation, pedestrian sidewalk, building block configuration, street design, urban corridors and green spaces are amongst parameters influencing the heat removal from the surfaces of building. Therefore, the airflow detail plays a key role in understanding how heat is exchanged between a street canyon and its environment. In many studies, the MCM models are the selected technique in investigating airflow details [20,21].

Using higher albedo (cool) materials and green surfaces decreases solar gain of a buildings' skin, resulting in moderation of the UHI. Thus, urban-scale models are highly preferred when the studies are intended to represent the impact of an extensive deployment of cool or green materials on an urban climate [22•,23].

4.2. Health and comfort

Outdoor thermal and wind comfort during the exacerbated UHI by the local heat waves is a widely investigated subject [9]. In most of the studies, air temperature, moisture, and solar radiation in a city's courtyards, green-spaces, sidewalks and ponds are monitored with mobile and stationary stations to study the impact of the UHI on pedestrians' comfort. Furthermore, simulation techniques are utilized to estimate the reduction in heat related mortality rate by applying mitigation strategies [24••]. Moreover, field surveys are broadly conducted to help researchers to analyze and convert the obtained datasets to comfort indices such as physiological equivalent temperature (PET) [25,26].

4.3. UHI spatial–temporal variation

It is well-documented that the UHI effect significantly varies with the location within a city and time of day. Many studies thus focus on monitoring and modeling this spatial–temporal variation. Since the complexity and diversity of the contributing parameters cannot be easily modeled by deterministic approaches, the majority of models are developed based on the stochastic techniques such as regression method, which are supported by enormous datasets obtained from remote sensing imagery [27–29]. The majority of the studies confirm relationships between surface/air temperature and corresponding urban land characteristics.

4.4. Model evaluation and enhancement

Multi-scale models are formed from integration of different types of models in order to cover the existing gap between them. A higher resolution results in a large-scale area can be achieved using these models although the coupling technique still requires special considerations in balancing mass and heat amongst the models. For example, [30] obtained a better accuracy by integrating BEM, UCM, and MM models to estimate summer waste heat emissions from anthropogenic activities.

4.5. Future temperature forecast

Prediction of the UHI impact on future indoor and outdoor air temperature helps to adapt new strategies and policies in the design and retrofit of existing and planned buildings. Stochastic models developed based on ANN and regression techniques are

Table 1
Recent studies on modeling of the UHI.

Name	Purpose	Location	Methodology	Significant finding
Urban ventilation and surface material alteration				
[36]	Impact of the greenspace on night-time UHI intensity reduction	London, UK	Mobile measurement + a developed correlation	Using meteorological stations close to urban greenspace can underestimate urban heat island intensity due to the cooling effect of the greenspace.
[23]	The potential benefit of the green roof retrofit in a densely urban district	Hong Kong, China	3D sun-path and shading models	This preliminary study suggests that the green roof retrofit is feasible in Mongkok, China.
[22•]	Evaluation of the potential atmospheric effects of solar PV deployment	Los Angeles, USA	MM (MM5)	No adverse impacts on air temperature and UHIs are predicted from large scale PV deployment.
[21]	Effects of urban geometry on urban ventilation	Muar, Malaysia	MCM-CFD (IES)	Step up configuration was found to be most effective in improving the overall natural ventilation.
[20]	Investigation of various UHI mitigation scenarios	Phoenix, USA	MCM-CFD (ENVI-met)	Increasing the amount of shade trees, vegetation and permeable surfaces can decrease the UHI.
Health and comfort				
[26]	Outdoor thermal comfort	Rotterdam, Netherlands	A network of 14 weather stations + PET evaluation	Differences in air humidity and global radiation in urban areas are relatively small and have no notable influence on the magnitude of PET.
[25]	Outdoor comfort	Glasgow, UK	Mobile	measurement + temperatur-humidity-sun-wind and PET evaluation
	Urban sites will have fewer days of cold discomfort, more days of neutral thermal sensation and slightly higher warm discomfort.			
[37]	Outdoor thermal comfort	De Bilt, Netherlands	MCM-CFD (ENVI-met + RayMan) + field measurement + PET evaluation	The courtyard provides a more protected microclimate which has less solar radiation in summer.
[24••]	The potential benefit of urban vegetation in reducing heat related mortality	Melbourne, Australia	BES (AccuRate) + UCM + MM (TAPM)	It is estimated that around 5–28% reduction in heat related mortality rate can be obtained by doubling the city's vegetation coverage.
UHI spatial–temporal variation				
[38]	Exploring nonlinear relationships between LST and landscape characteristics	Guangzhou, China	Satellite remote sensing + regression method	The relationships between LST and corresponding urban biophysical composition are characterized.
[39]	Exploring relationship between mean air temperature and related influence factors	Ljutomer, Slovenia	Stationary and mobile measurement + regression method	Variables, i.e. distance to urban area, topographic position index, land-cover diversity, building volume/area and northness are contributing in spatial UHI.
[29]	Exploring the overall variation of the intensity and distribution of the UHI	Beijing, China	Satellite remote sensing (MODIS-Terra/Aqua) + Gaussian volume model	The trajectory of UHI centroid provides insights for the spatial–temporal variation of the urban thermal environment.
[28]	Estimation of the near-surface air and dew-point temperatures	Phoenix, Houston, and Chicago, USA Toronto, Canada	Satellite remote sensing (MODIS-Terra/Aqua) + ground observations	Relationship between the air temperature and the urban fractions is investigated.
[27]	Prediction of the peak daytime air temperature	Vancouver, Canada	Satellite remote sensing (TM/ETM) + regression method + ground observations	The spatial distribution of Tmax in a large metropolitan area is mapped.
[40]	Exploring the UHI intensity	Chicago, USA	Weather stations + stationary measurement	The effect of fourteen variables on spatial–temporal variation of air temperature is investigated.
[41]	Exploring the relationships between a set of land cover types and the surface temperature	TaoYuan, Taiwan	Satellite remote sensing (SPOT and NOAA)	A newly developed geographically weighted regression (GWR) model has better performance than conventional regression models.
[42]	Simulation of the UHI during a heat wave	Hangzhou, China	Satellite remote sensing (MODIS) + MM (WRF) + UCM + ground observations	Urban areas have higher near-surface air temperatures during heat waves, especifically during night-time.
[19•]	Exploring the urban determinants of the UHI	Columbus, USA	Satellite remote sensing (Landsat) + LIDAR + spatial regression	Effects of five urban characteristics captured over regular grids: building roof-top areas, vegetation index, solar radiations, sky view factor, and water.

Table 1 (*Continued*)

Name	Purpose	Location	Methodology	Significant finding
[43]	Day to day temperature variation	Multiple North American cities	Weather station (National Climate Data and Information Archive)	Urban effects using the thermal response of a modified land surface is identified.
Model evaluation and enhancement				
[30]	Estimation of summer waste heat emissions from anthropogenic activities	Phoenix, USA	BEM and UCM (BEP/BEM) + MM (WRF)	The spatial–temporal analysis of anthropogenic heat may influence the form and intensity of the Phoenix UHI.
[44]	Modeling of the spatial–temporal variation of the UHI	Athens, Greece	Satellite remote sensing (MODIS) + MM (WRF) + ground observation	The performance of the modeling system was evaluated.
[45]	Investigation of the thermal characteristics of the outdoor space	Chania, Greece	MCM (PHOENICS) + terrestrial Laser Scanners (TLS)	A model based on the integration of Terrestrial Laser Scanners (TLS), aerial ortho-photography, and computational fluid dynamics (CFD) is developed.
[46]	Identifying the dominant factors involved in the night-time UHI	–	MCM-CFD + radiative model	A subtle and complex interplay between all physical processes is observed.
Future temperature forecast				
[47]	Investigation of the spatial and temporal of the UHI in future	Stuttgart, Germany	5 weather stations + climate change model (RT2B)	The amount of days with heat stress (PET P 35 C) is estimated to increase by about 17 days until the end of the 21st century.
[13]	Exploring the role of current and future global/local warming on indoor thermal environments	Chicago and Houston, USA	BEM (EnergyPlus) + global climate projections dataset	Under hot summer conditions interior air temperatures rise to very uncomfortable levels within the first day of the air conditioning system failure.
[31••]	Prediction of the indoor air temperature during the UHI	Montreal, Canada	Indoor temperature measurement + ANN	The thermally vulnerable areas can be identified during the exacerbated UHI.
[48]	Prediction of urban canopy level air temperature	Singapore, Singapore	Weather station + UCM	An improved version of Urban Weather Generator (UWG) is evaluated.
[32]	Forecasting the maximum daily precipitation for the next coming year	Athens, Greece	National Observatory of Athens (NOA) + ANN	The developed ANN seems to overestimate the maximum daily precipitation totals appeared in 1988 while underestimating the maximum in 1999.
Building energy saving				
[12•]	Energy efficiency of buildings during the UHI	15 cities across different climate zones in the U.S.	BEM (EnergyPlus) + UCM (TEB–ISBA)	The UHI leads to significant changes in building cooling and heating energy use and demand.
[35]	Cooling energy savings due to night-ventilation during the UHI	Amsterdam, Netherland Milan and Rome, Italy	BEM (EnergyPlus) + MCM (AFN)	The study concludes that a detailed description of the surroundings is crucial to assess the suitability of passive cooling solutions.
[34]	Evaluation of the BEM implemented in a UCM model	Paris, France	UCM (TEB) + BEM (EnergyPlus)	The sensitivity of building energy models to the outdoor energy balance is investigated.
[49]	Comparison of both heating and cooling demands under current and future conditions	Vienna, Austria	BEM (TAS)	Energy efficiency of a building envelope and climate have to be viewed jointly to gain a reliable picture of the future energy performance of the building.
[33]	Heating and cooling energy calculation of a university building	Modena, Italy	BEM (TRNSYS) + two weather stations	UHI mitigation could achieve significant energy savings on summertime cooling energy demand.

more utilized in the projection of future temperature within the cities in accordance to their built area [31••,32]. In general, these models exhibit a promising performance in prediction of the future UHI.

4.6. Building energy saving

The UHI considerably impacts the heating/cooling energy demand of buildings. This comparison is conducted in many research case studies in various locations and climates [12•]. Moreover, the importance of the UHI mitigation strategies in the reduction of these energy demands is widely studied [33]. These works conclude that the influence of the surrounding built area is a crucial factor in building energy calculation [34,35].

5. Conclusion

The application of different scale models in the UHI studies is explained. The theme of studies is prioritized with representing sample works conducted in the last two years for each category. While building and microclimate models have higher resolution in the urban canopy layer, they cannot spatially be extended to cover the entire area of a city due to the extensive computational cost and complexity of the important parameters. Despite the capability of meso-scale models in investigation of the large-scale effect of the UHI, their accuracy is not enough to provide details about the urban canopy layer. This gap thus requires further research to develop spatially and computationally efficient models.

Acknowledgment

The author would like to express gratitude to his mentor in Building Physics, Prof. Fariborz Haghighat, full professor at Concordia University, Canada.

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