Review of Urban Heat Island and Building Energy Modeling Approaches

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In this paper, a review of the current literature in modeling urban heat island (UHI) phenomena including its main causes and effects is summarized. The main goal of the review is to assess the current modeling capabilities to accurately determine the impacts of UHI on outdoor comfort levels and urban building energy demands. In particular, the analysis techniques and modeling approaches are overviewed to estimate the mutual thermal interactions between urban atmosphere and buildings. In addition, the applications and the limitations of various modeling methods are discussed to predict outdoor thermal comfort and urban building energy consumption. The specific capabilities of the reviewed modeling approaches are highlighted to assess the effectiveness of mitigation strategies of the UHI effects. As part of the review analysis, recommendations are outlined to improve current modeling approaches to predict more accurately the impacts of UHI phenomena on urban building energy performance. [DOI: 10.1115/1.4053677]

Keywords: air conditioning, atmospheric layers, building energy performance, multi-scale analysis, outdoor thermal comfort, UHI mitigation solution, UHI modeling approaches, urban environment, urban heat island (UHI) effects

1 Background

There has been a significant migration of world population from rural areas to urban areas during the last several decades. Indeed, people are moving to cities in the hope to seek better options for jobs, education, and health. Since 2007, the urban population exceeds the rural population worldwide [1]. Only 20% of the world population was living in urban areas one century ago [2]. Through the development of several mega cities in the last few decades, it is expected that 70% of world population to live in urban cities by 2050 [2]. Based on the United Nations projections [3], the number of cities with populations above 500,000 inhabitants will be increasing to 1393 by 2030 and thus more than doubles the number of these large cities that were available in 1990. Mega cities (more than 10 million population) will increase to about 41 cities in 2030 from 10 cities in 1990. Based on a study by Madlener and Sunak [4], the urban population is expected to reach 5.3 billion from 2.6 in less developed countries. Specifically, less developed countries are projected to have 3.3% per annum urban growth rate from 2010 to 2050 [4]. As indicated by several reported analyses, urbanization is leading the world to the irreversible path toward the expansion and the creation of higher density cities [5]. While this path may result in some improvement of standard of living and economic prosperity, the increase in urban population density could have substantial negative effects on the global climate. Indeed, urbanization has shown to increase energy consumption due to changes in life style, transportation, type of residential units, and human behavior patterns [4]. Increasing energy demand means more fossil fuel burning that leads to more greenhouse gas emissions (i.e., CO_2 emissions) and thus global warming.

Some of the challenges that urban planners face include achieving sustainable mobility and transport, reducing energy consumption of the building stock, and increasing renewable energy production [4]. In addition, one of the well-known problems of urbanization is the noticeable increase in ambient air temperature of urban centers compared with rural areas. This phenomenon is called urban heat island (UHI). UHI can exist in 1 km^2 cities [6]. Several studies have analyzed this phenomenon and its effects using different approaches. These studies mainly aim to identify and understand the main factors that affect UHI development, urban center ambient temperature variations, main UHI impacts, as well as effective UHI mitigation options. Landsberg authored a pioneering book on the Urban Climate in 1981 [7] describing urban energy fluxes, urban heat island, urban temperature, and wind modeling. In 2001, Arnfield reviewed two decades of research studies on UHI effects and energy and water exchanges [8]. In his review, he highlighted the importance of understanding and modeling urban climatology with its different scales (i.e., urban canopy layer (UCL) and urban boundary layer (UBL)). The review pinpointed that validation of numerical simulation models lags the development of the numerical simulation tools due to difficulties of real measurements.

Stewart [9] performed a systematic review of UHI modeling methods reported in the literature between 1950 and 2007. He concluded that, although some outstanding studies are available, the vast majority of UHI studies lacks rigor and do not meet high-quality standards due to two main weakness areas. The first weakness is the insufficient control in most studies of the confounding effects of different factors such as weather, relief, and time on the magnitude of UHI phenomenon. The other weakness is the lack of reported details on the methodologies and testing approaches including measurement conditions, instrument specifications, and limitations of the data collection. Stewart offered some recommendations to improve the quality of UHI studies. Among these recommendations it is important to use data with lower temporal and spatial resolutions to achieve more controlled measurements. In addition, the following standardized guidelines set by Aguilar et al. [10] and Oke [11] is recommended to enhance the scientific quality of UHI-related analyses. Furthermore, Stewart recommends researchers to disclose the limitations of their studies and the details of data collection conditions.

Outdoor air comfort, UHI mortality, and its health effects, as well as energy consumption of the built environment have been among the main focuses of the reported impacts of UHI studies [12]. Although maximum UHI temperature increases occur during the afternoon periods, both daytime and nighttime temperature variations can have significant impacts. Kalkstein and Davis [13]

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found that warm nighttime temperature is a strong predictor of heat related mortality. It has been reported that 4 °C increase in mean ambient air temperature could rise heat related deaths in Stockholm, Sweden, by 5% [14]. In addition, it has been reported that heat disorder mortality in 2010 is about 8.5 times than that observed in 1990 for Japan [15]. Moreover, wet bulb globe temperature that combines dry bulb, wet bulb, and globe temperatures is found to be a useful indicator to model heat stress. In particular, Ohashi et al. [15] noted that for Japan, wet bulb globe temperature between 28 °C and 31 °C corresponds to severe warming level while temperatures above 31 °C are considered to be at the danger level. Regarding the impact of UHI phenomenon on energy consumption, some studies show that an increase of the maximum UHI temperature by 1 K could increase the cooling energy consumption for residential buildings by 5% [16]. Moreover, Kolokotroni et al. [17] listed three interconnected impacts of variations in outdoor air temperatures including indoor and outdoor thermal comfort changes, energy consumption of buildings, and health issues such as heat related mortality. Moreover, reducing nighttime urban air temperatures by about 1 °C could reduce electricity consumption by up to 1300 MWh per day in Phoenix, AZ [18].

In this paper, a systematic review of the current literature in modeling UHI phenomena including its main causes and effects is summarized. First, the urban atmosphere is briefly described including the formation of atmospheric layers above an urban environment. Then, the main causes of UHI development and its intensity are discussed with specific references to various reported analyses and studies. After outlining common analysis approaches of the UHI phenomena, some of its major effects are described including outdoor thermal comfort and energy performance of urban built environment. Finally, UHI mitigation strategies are presented with their potential effectiveness based on reported evaluation analyses. The main goal of the review is to determine research gaps in modeling approaches to accurately determine the UHI effects and associated mitigation strategies on the energy performance of urban buildings.

2 Description of Urban Atmosphere

Understanding urban atmosphere formation is essential for modeling and thus investigating the UHI phenomenon and its impacts on urban built environment. The atmosphere for an urban area can be divided into two or three distinct layers depending on the weather characteristics and climatic conditions such as wind speed, air temperature, flow pattern, and other factors as illustrated in Fig. 1. Each layer has spatial and temporal flow characteristics different from those of other layers. The characteristics of the UBL are governed by nature of general urban surface, while the UCL is governed by microscale processes between buildings and other urban canyon surfaces [19]. The UBL thickness can range from tens of meters during nighttime to hundreds of meters during daytime. The canopy layer height is the same as that of the highest building [20]. Urban plume is a layer above the rural area (which is adjacent and downwind to the urban area) where the weather is still affected by the urban boundary layer and it could extend to several km downwind with conditions similar but less obvious than urban climate [19].

The formation of UCL and UBL above a city can have significant impacts on outdoor air temperatures and thermal comfort levels. For instance, at a mesoscale level, the effect of AC system heat waste is found to be larger during nighttime because of the low height of UBL that is about few hundred meters compared with several kilometers during daytime [18]. In addition, some studies indicated that the impact of AC systems on the region's climate is determined by the height of planetary boundary layer not the outdoor temperature [18]. Furthermore, de Munck et al. [21] mentioned that nocturnal increase in air temperature is higher than that observed during the day due to shallower atmospheric boundary layer which is about few hundred meters compared with several kilometers during the day. However, several types of heat islands including surface heat island (SHI), heat island of the urban canopy layer and urban boundary layer heat island occur at different time and cover different areas [19,22]. The main mechanisms to generate UHI for urban boundary layer and for urban canopy layer are discussed in the reported literature [19].

3 Causes for Urban Heat Island Development

Many studies have investigated conditions and variables that cause UHI formation and enhance its intensity. Coseo and Larsen [23] did analyze how land use, land cover, building configuration, and adjacent heat sources and sinks affect UHI in Chicago, IL. Their study investigated about 14 independent variables that may explain UHI including average building size, percent impervious surface, percent tree canopy, building height by block, street aspect ratio, and street orientation. Based on Brian Stone [24], four main city characteristics contribute to the development of UHI including reduction of evaporative cooling due to lack of vegetation; low surface reflectivity due to dark pavements, streets and buildings; vertical surfaces that cause solar radiation trapping; and waste heat or anthropogenic heat from buildings cooling systems, power plants and industries. Coseo and Larsen [23] have found that waste heat sources from industrial processes, air conditioning and vehicular traffic in addition to wind patterns, and strategic placement of vegetative buffers can be significant factors in the development of UHI and should receive more attention in UHI

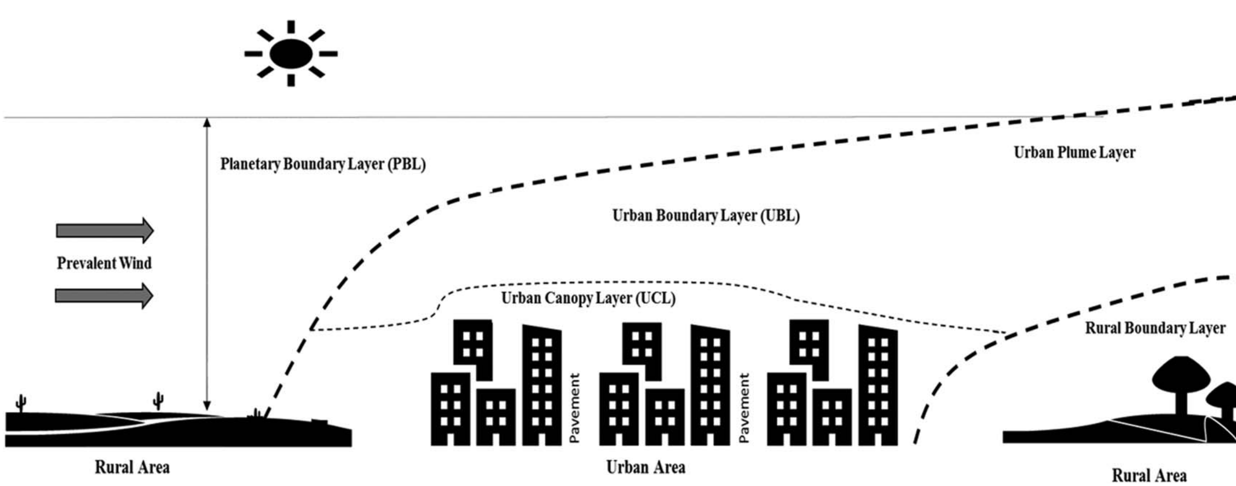

Fig. 1 Typical atmospheric layers considered for urban and rural areas

research. In particular, vegetation in high-density urban areas can reduce solar radiation absorption due shading and evaporation [5]. Salamanca et al. [18] found that waste heat released form AC systems could increase the mean nighttime ambient air temperatures from 1.0 °C to 1.5 °C. In addition, the study reported that the effects of AC waste heat are not significant during the daytime although the AC heat flux is maximum.

Table 1 lists the main reported urban features and their impacts on energy balance within urban environment as well as their effects in the development of the UHI phenomena.

3.1 Impact of Urban Surfaces. The characteristics of ground surfaces are often different for urban areas and for rural areas. For rural areas, the ground surface is usually pervious such as soil, grass, and forest. The surface in rural areas can be also water body like river, sea, and lake. On the other hand, ground surfaces in urban areas are mostly made up of asphalt (i.e., streets and pavements) or concrete (i.e., buildings and parking lots). These types of surfaces are impervious and thus they do not retain water and no evaporation could occur. Evaporation of water stored in the surface has an evaporative cooling effect. Thus, ground surface evaporation increases sensible heat flux and reduces latent heat flux [5]. Using impermeable materials in streets and pavements means that rain water drains rapidly through deep sewer systems preventing surface evaporation that leads to a reduction in latent heat flux and an increase in sensible heat flux, long wave emissions, and conduction through the ground surfaces [19]. Surface albedo in urban areas is also another factor that could affect the microclimate compared with rural areas. Albedo is the ratio of the reflected shortwave radiation to the incident solar radiation [20]. As the surface is darker, it absorbs and stores more shortwave and long wave radiations such as radiation from the sun and radiation reflected from other surfaces. The stored thermal energy is then emitted during evenings or nights resulting in an increase in ambient air temperatures. Shortwave radiation is within the spectrum range of 0.3 to 2.5 μm, while long wave radiation is from 2.5 to 18 μm [25]. Furthermore, urban shapes and materials induce a multiple reflection of the radiation which increases the radiation absorbance in the urban areas forming what it is referred to as solar trapping phenomena [25]. The street canyon orientation, the height of buildings, and the distance between structures are also factors that affect energy balance within the urban areas. These factors affect the amount of solar energy that is trapped within urban areas. In addition, solar reflectance within the urban areas is found to be important for thermal comfort assessments not just because of the thermal energy it carries but also due to the glare effect that could reduce the outdoor comfort for the pedestrians [26].

3.2 Anthropogenic Heat Emissions. Anthropogenic heat can enhance the development of UHI by increasing turbulent vertical mixing and the size of the urban boundary layer [27]. It has been found that anthropogenic heat from only energy consumption may contribute up to 1 K increase in outdoor ambient air temperatures during winter of mid and high latitudes cities and during autumn of north America and Eurasia urban centers [28]. The main sources of anthropogenic emissions are power plants, vehicles, human metabolism, residential and commercial buildings, and factories [29]. Generally, outdoor human metabolism can be ignored as it forms less than 1% of total anthropogenic heat of the city [29]. Chow et al. [27] reported that anthropogenic fluxes are greater during winter for cities with mid/high latitudes where energy required for building heating during wintertime is more than that needed for building cooling during summertime. For cities located in hot climates, where energy consumption for space cooling energy is higher than that for space heating, the anthropogenic fluxes are greater during the summer periods. Based on a review analysis by Sailor [29], anthropogenic emissions have two main mechanisms for each of the two components (sensible heat and moisture emissions). For sensible heat component, emissions can occur directly through air conditioning systems, heating equipment, chimneys, or tailpipes. Moreover, indirect sensible heat emissions can occur from building envelope elements by conduction and then to the urban atmosphere by convection and radiation [29]. On the other hand, Sailor indicated that moisture heat component can be emitted through evaporative cooling devices (latent heating for urban environment), or through chemical reactions such as combustion of hydrocarbon fuels (however, this cannot be considered latent heating as the resulted water vapor is from the chemical reaction and not from phase change). The review study also reveals that anthropogenic emissions (heat or

Table 1 Main urban features and their impacts as well as their UHI development effects

Main category	Factors	Impacts	UHI effects
Urban surfaces	Characteristics of buildings and pavements surfaces like (thermal mass, albedo, roughness, and else)	• Absorb and store heat • Increase reflective surface area • Reduce water permeability of ground surface	• Increase heat storage • Increase shortwave radiation • Reduce evapotranspiration and its cooling effect
Vegetation	Canyon vegetation, parks, and/or roof vegetation	• Increase shading on surfaces below • Increase water permeability of ground surface	• Reduce absorbed solar radiation and thus reduce urban surface heat flux • Increase evapotranspiration and its cooling effect
Anthropogenic heat flux	Air conditioning systems Vehicular traffic	• Reject heat (HVAC systems) • Increase heat emissions • Increase air pollution	• Increase anthropogenic heat intake • Increase anthropogenic heat intake • Increase absorption of shortwave radiation
	People density	• Increase heat emissions through human metabolism	• Increase anthropogenic heat intake
	Power plants and factories	• Increase heat emissions • Increase air pollution	• Increase anthropogenic heat intake • Increase absorption of • Shortwave radiation
Urban morphology	Building distribution, building shape, Urban canyon aspect ratio, and canyon geometry	• Change airflow patterns • Reduce sky view factor • Impact the solar radiation budget	• Lower convective heat transport • Reduce longwave radiation loss to the sky • Could increase or decrease the absorbed solar radiation
PV deployment	PV surface characteristic and shading impact	• Increase shading on surface below • Reduce sky view of the surface below • Absorbs solar radiation	• Might increase or reduce the total heat flux to the atmosphere (based on the characteristics of urban surfaces before PV deployment)

moisture) can significantly change temporally and spatially. However, Sailor found that most of the studies ignore the moisture emissions since they are difficult to estimate. Furthermore, Sailor noted that heating, ventilating, and air conditioning (HVAC) systems are the largest contributor in the anthropogenic emissions from buildings (with peak loads occurring between 3 pm and 5 pm during the summer) and it is therefore important to specify the vertical location of the heat exchange between the buildings and their surrounding environment [29]. However, Sailor has indicated that there are three main methods for estimating anthropogenic emissions including inventory approaches, energy budget closures, and building energy models with each method having specific advantages and limitations [29].

Chow et al. [27] used multi-method and multi-scale approach to estimate citywide anthropogenic heat fluxes in Phoenix, AZ. The study focused on three sources of anthropogenic heat waste consisting of human metabolism, vehicular traffic volume, and air conditioning from buildings. For the first two sources, existing databases used via top-down inventory methods are considered to estimate their impact. For energy waste from air conditioning systems, BEM + BEP (building energy modeling integrated with multilayer urban canopy parameterization (UCP)) is utilized coupled with regional climate modeling. However, the analysis approach depends on traffic, population, and electrical consumption data that may not be available for different locations. The reported study considers mesoscale analysis approach but with limited integration and no interactive effects between the various factors. Quah and Roth [30] used inventory-based modeling to estimate anthropogenic heating for a tropical city in Singapore. The study found that anthropogenic heat is an important factor in urban energy balance of the commercial district as it has nighttime values almost equal to those of the net radiation. In their study, all energy uses are converted to anthropogenic heat. In addition, no time lag between energy consumptions and heat emissions of the buildings is considered. However, inventory-based approach depends on data such as utility consumptions and bills which can be a significant challenge in several countries.

Another integration attempt is reported to evaluate the effects of anthropogenic heat fluxes in Phoenix, AZ [18]. In this specific study, multilayer building energy parameterization BEP + BEM coupled to the atmospheric WRF model to predict near-surface climatology considering the effects of AC system waste heat on outdoor air temperatures for Phoenix, AZ using a mesoscale analysis. Urban canyon parameterization can estimate the radiation trapped and shadowing effect in urban canyon as the existence of obstructions of open sky from buildings. In addition, urban canopy parameterization represents the urban domain in better way as it treats vertical and horizontal surfaces separately [18]. This study stated that, waste heat could exacerbate the nocturnal UHI effects where it could increase the 2 m level urban air temperature by up to 1 °C due to AC heat waste in hot/dry cities. However, the simulation in this study has been done for ten of the hottest days in the year that maybe due to the high computational cost.

A mesoscale analysis for estimating the impact of waste heat from AC systems on the outdoor atmosphere in a city scale has been reported for Paris, France [21]. In this study, the mesoscale meteorological model (MESO-NH) and Town Energy Balance (TEB) have been coupled to estimate the impact on street temperatures of air conditioning systems in Paris during six hot days during a heat wave period. TEB is based on 2D approximation canopy model formed by three types of surfaces, walls, roofs, and roads [16]. It is initially developed to estimate water and energy exchanges between urban surfaces and urban environment accounting for radiative trapping and shadow effects of the 3D geometry urban area [31]. TEB is significantly advanced for modeling energy budgets and turbulent processes in street canyons, but it has very limited capabilities in building energy modeling and ignores in particular internal loads within the building, shortwave heating of internal spaces, and air exchanges between the building and its outdoor atmosphere [29]. However, de Munck et al. [21] found that evaporative cooling has lower effect on increasing the urban canyon air temperature, but more investigation about its impact on humid city is needed. In addition, dry AC systems found to be the worse type of air conditioning where it has the greatest increase in street air temperature and most impact on nocturnal UHI.

In another mesoscale study, electrical consumption of urban air conditioning has been simulated using weather forecasting model coupled to multilayer building energy scheme [32]. In semi-arid regions, the study found that electricity consumption during the summer is more than twice that during moderate seasons. However, the study indicated that it is important to account for the anthropogenic heat explicitly as it affects the urban microclimate.

3.3 Impact of Urban Morphology. Because of the complexity of modeling city-scale thermal interactions, some mesoscale models use UCP [33], a simplified approach considered to represent some parameters within urban areas [34]. One of the simplifications made in such models is the use of mean values of width and height for buildings and streets. Based on Martilli [34], if the total fluxes of sensible and latent heat and momentum of the simplified morphology are similar to those for the real morphology then the simplified modeling represents adequately the real urban area. In the Martilli study, two techniques (2D simplified morphology and 3D regular simplified morphology) were compared with find the mean street width and the mean building width [34]. The study found that 2D simplified morphology is better than 3D morphology in terms of reproducing the real sky view factors.

Allegrini et al. [35] studied heat fluxes in urban environment with generic building configurations by using coupled computational fluid dynamics (CFD) analysis and building energy modeling. They used one-way coupled building energy and CFD simulations. Surface temperatures are determined and used in the CFD simulations that predict the temperature and flow fields for further understanding of the mechanisms of heat removal in urban city. CitySim is used for building energy simulation because of its capability of modeling energy fluxes for urban areas ranging from small neighborhoods to entire urban centers. Heat through the walls is estimated using RC (resistor-capacitor) thermal networks. In addition to their simplicity, the ability to efficiently find solutions with numerical programs and the use of fundamental physical relations are the main benefits of using RC modeling approach [36]. However, Allegrini et al. found that wind direction plays a significant role in estimating heat fluxes within urban areas [35]. The study recommends the use of detailed input data including several wind velocities, oblique flow directions, and building geometric characteristics, as well as the use of weather data for an entire year. They also stated that CFD analysis could provide accurate information on the ventilation patterns of the urban areas.

Thapar and Yannas [37] studied the effects of the urban form, vegetation, and water pods on the microclimate of the urban area in Dubai, UAE. These factors have been investigated using field measurements and ENVI-met model to simulate the microclimate. ENVI-met is a simulation tool for microclimate analysis with the ability to model air flows around and between buildings, exchange processes at ground surfaces and building walls, fundamental mechanisms of building physics, impacts of vegetation coverage, and other phenomena [38]. ENVI-met is a microclimate 3D simulation tool that can also account for the interactions between surface-plant and air within urban areas [39]. It can describe turbulence flows, radiation fluxes within urban canyons, turbulent transports of sensible and latent heat, and the impacts of vegetation [5]. Although Thapar and Yannas found differences between measured and modeled temperatures, they concluded that courtyard urban forms can provide the lowest outdoor air temperatures [37]. In addition, vegetation coverage and existence of water pods have cooling benefits on the microclimate. The study also recommends incorporating shaded and ventilated spaces in the urban areas. Some reported studies specific to urban forms analyzed the effects of wind speed in between and around the buildings on mitigating the UHI in city centers [40]. In the study, Integrated Environmental Solutions (IES) Virtual Environment and MicroFlo analysis tool has been used to simulate the wind flow between or around the buildings. The study has been conducted for a tropical city, Muar, in Malaysia. The study found that increasing the density and height of buildings can increase the UHI magnitude.

Gros et al. [41] assessed the interactions between buildings and their microscale surrounding using ENviBatE and SOLENE-Microclimate simulation tools. This study has been conducted for a zero-carbon district at the design stage in La Rochelle, France. The interactions considered in this study are not totally integrated (i.e., no reciprocal and dynamic interactions). However, the study focused on the effects of urban morphology on both energy consumption and urban microclimate. It showed that for a densified district, a decrease of about 80% and 7% decreases in wind velocities and solar irradiations on buildings, respectively. The study compared two models (CFD coupled to SOLENE and QUIC software) to compute airflows in the urban domain. It found that QUIC software provides accurate and fast results compared with the CFD-based analysis. SOLENE software is estimated to take about half day of computing time for 3 weeks' period simulation considering only one building in order to calculate indoor temperatures and building energy demands. On the other side, EnviBatE is found to take about half day of computing time to simulate a period of 1 year considering all the buildings.

Photon tracking modeling approach based on the Monte Carlo method has been used to calculate net shortwave and long wave radiation fluxes within the urban canopy for different design configurations [20]. Four factors have been considered in this study by varying urban canopy configurations including building coverage, building height distribution, canopy height, and orientation of roads. The urban albedo is found to increase as the building height is reduced, open spaces are increased and/or uniformity of building height are established. In addition, the study indicates that the albedo increases as the solar altitude increases [20].

The cooling effects of greening in high-density cities have been assessed through a case study of Hong Kong [42]. A set of parametric analyses have been conducted for this study to find optimal locations, levels, and types of vegetation for urban planning. The study used the microclimate model ENVI-met. It is found that roof greening is not beneficial for human thermal comfort in high-rise and high-density urban centers. Indeed, greening on top of buildings with the ratio of building height to street width exceeds one has low cooling effects on outdoor human thermal comfort. In addition, the study indicated that for cooling pedestrian areas, trees are more effective than grass as they provide more shading benefits. Furthermore, this study recommended that 33% of urban areas be planted by trees to reduce pedestrian level air temperatures by 1 °C when built area fraction is about 44%. However, the study did not include the effects of greening on energy consumption of the buildings and thermal interactions between buildings.

3.4 Impact of Air Flows. Wind flows can be significant in UHI forming by exchanging heat into and from urban surfaces and by providing urban ventilation. Air flows within urban areas have been reported by several studies to have lower speeds compared with those for rural areas due to obstacles and friction forces prevalent in urban centers [19,40,43]. For instance, Kuttler [19] indicated that wind speed at surface level can be higher in urban areas than that in rural areas during nighttime and early morning hours for calm cloudless weather conditions. Mass and momentum exchange rates between UCL and UBL contribute to remove heat from urban canopy layer. When this heat exchange rate decreases, the heat removal in UCL also decreases [43]. However, airflows within urban areas are difficult to estimate especially with other methods other than CFD models. Several studies have investigated airflows in street canyons considering a wide range of factors including building configurations, street aspect ratios, atmospheric wind directions, turbulence intensities, traffic flows, and thermal stratifications [44]. Most of the reported studies evaluated airflow patterns over urban street canyons [44]. In particular, perpendicular wind airflows over street canyons are considered since they constitute the worst case for urban ventilation, heat removal, and pollution dispersion [43–45]. Steep variations in horizontal velocity between the external winds and airflows at the top of street canyons cause shear forces that drive the airflows over street canyons perpendicular to the freestream [46]. But it also has been reported that this large difference between the velocities in this case (wind direction as normal to street axis) increases the rooftop level vertical turbulent exchange rate of the horizontal momentum [43]. Oke [47] suggests three flow regimes when wind blows perpendicularly on street canyon and are defined by the aspect ratio and the street length. For instance, for street length of $4H$ (H is the height of the buildings) and if the aspect ratio H/W (W is the canyon width) is 0.33, the isolated roughness flow (IRF) occurs with no interactions between the flow fields resulted by the buildings located along the parallel streets. If the aspect ratio ranges from 0.33 to about 0.75, then the flow regime is defined as the wake interference flow (WIF) with the wake flow in front of downwind buildings is disturbed by the wake flow behind the upwind buildings. As the aspect ratio exceeds 0.75, the third regime that is skimming flow (SF) is formed with stable air circulation occurring and the bulk of the external flow not entering the street canyon. Different air vortices may occur as the aspect ratio increases. Other studies have found different conditions for these flow regimes to occur. In particular, Sini et al. [48] have indicated that for aspect ratio H/W of 0.11 to 0.125 the flow transitions transfer from IRF to WIF. In addition, it is found that when the aspect ratio is greater than 0.67, the flow changes from WIF to SF with one recirculation until the threshold of 1.67 is reached when two or three circulations occur. Furthermore, Kim and Baik [49] found that for skimming flows, one vortex is formed when the aspect ratio is between 0.6 and 1.2, two vortices when the aspect ratio ranges from 1.4 to 3.2, and three vortices for aspect ratio between 3.4 and 3.6. Baik and Kim [45] found that, an aspect ratio above 0.5 is required for skimming flow with one vortex; an aspect ratio from 1.5 to 2.5 for two vortices; and an aspect ratio of 3.5 for three vortices. These values do not change dramatically between reported studies. However, He at al. [50] found that two vortices flow patterns appear for aspect ratio of 5–6 and single vortex for aspect ratio of 1–4.

Several analysis approaches have been used to investigate wind induced airflow and pollution concentration in street canyons. These approaches include laboratory testing setup using wind tunnel and water channel, field observation and measurements, and CFD modeling [44]. In particular, CFD-based approaches to model flow and pollutant in urban streets utilize Reynolds-averaged Navier–Stokes (RANS), large-eddy simulation (LES), and direct numerical simulation. LES modeling is becoming more common in recent years due to the development of high-speed computational capabilities. These models are mostly used to model turbulence in fluids to evaluate air movements between obstacles such as the case of urban areas. For example, Raasch and Schröter developed an LES model called PALM operated on massively parallel computers, [51]. This model had been used by Keck et al., [52] to study the pedestrian level ventilation in the city of Macau. The study investigated the impact of urban morphology and the planed reclamation places on the required ventilation rates.

Other street canyon models include reduced-scale, box, and Gaussian approaches by Vardoulakis et al. [53]. Based on their study, it has been reported that the strength of the vortices depends mostly on the external wind speeds at roof tops and on thermal effects induced by canyon surfaces in addition to the turbulence produced by moving vehicles. Understanding and estimating the wind speeds as well as mass and momentum exchanges during the design phase of urban planning can lead to what is called passive mitigation of UHI effects and pollutant concentrations by modifying urban layout morphology and surfaces materials [43]. Airflow in street canyons is found to be influenced by heating induced from the difference in temperatures between airflows and urban surfaces [48,49,54]. For instance, a numerical method with Reynold-averaged Navier–Stokes equations has been used for perpendicular airflows [48]. The analysis using this method indicated that, for skimming flow with one vortex, heating effects from leeward side and the street ground increase the intensity of the vortex inside the canyon while heating from windward side works against the vortex motion resulting in splitting the flow into a multi vortex pattern. Based on a wind tunnel based experimental analysis and numerical modeling, five flow regimes have been identified depending on the vortex number and type (i.e., thermal or mechanical) when canyon ground heating occurs [49]. Furthermore, Li et al. [54] has investigated the effect of heating the ground on the airflow within street canyon having an aspect ratio of 1 and a perpendicular freestream to street. The study found that when ground surface was heated, the mean flow in street canyon is no longer isolated from freestream and the magnitude of the mean flow and turbulence increases without a significant change in flow patterns.

Another factor that causes the heating air flows is associated with the temperature difference between air flow and urban surfaces induced from absorbed solar radiation. Nazarian and Kleissl [55] investigated the impact of solar insolation and inter-building shading on nonuniform thermal exchange and canyon ventilation. The analysis found that during daytime, windward walls have larger convective heat transfer coefficients. In addition, the air exchange rate is found to increase when the wall heating dominates in cross stream canyon. Moreover, the analysis shows that temperature gradients and air exchanges in span-wise directions significantly affect the canyon vortex. The effects of heating multiple surfaces and in stream-wise canyons are also found to affect the canyon vortex. In contrast with the findings reported by other studies that only consider the ground heat of the streets, horizontal temperature gradient at the roof level was determined to decrease the vortex strength when ground heating of the canyon street is considered [55]. From the analysis results, Richardson number is found to be insufficient to describe atmospheric instability. Instead, an additional buoyancy parameter is needed to consider the orientation of the wall heating relative to the wind flow direction and the difference of horizontal temperatures within the canyon street. Based on the findings of the analysis, the orientation of urban canyon can affect significantly the air exchange during daytime [55]. Traffic flow also has been shown to have some impacts on the air flow within street canyon. In particular, Thaker and Gokhale [56] investigated the effects of traffic flow on air turbulence in street canyons and found that traffic flows can have a significant impact on air turbulence that can reduce pollutant and heat in urban canopy.

A simplified method to estimate bulk street canyon velocity as well as mass and momentum exchange rates between UCL and UBL is introduced by Hall et al. [43]. The method used an idealized canyon street model with a homogeneous urban morphology. Moreover, the method assumes that skin friction and exchange coefficients are mutually independent. In addition, it is indicated that street aspect ratio and exchange coefficient can be set to be mutually independent to achieve an acceptable accuracy. The results using the simplified method show that the length of the flow developed over urban area can span over hundreds of streets. Moreover, it is indicated that the urban center can be modeled using a fully developed wind flow [43]. Furthermore, it is indicated that the exchange coefficient depends only on neighborhood geometry and does not change with the flow Reynolds number. Therefore, the bulk longitudinal velocity in street canyon can be determined using few parameters including freestream velocity, street geometry, street surfaces friction coefficient, and exchange coefficient. However, it has been reported that average wind velocity in street segments between intersections can be the same as that estimated in infinitely long streets for specific wind directions. Otherwise, the wind velocity is significantly lower for finite street lengths [46].

Moreover, air flows that are angled with the axis of streets have been investigated by several studies. In fact, wind direction is one of the terms that characterize the average velocity in the street in addition to the intensity of the external wind and the geometry of the street [46]. Spiral wind flows in street canyons are induced by external wind flows angled with the axis of streets due to the reflection of the wind off the windward side of the canyon [53]. Flows in street canyon induced by oblique external wind flows are linear combination of parallel and perpendicular components of the external wind [57]. In particular, it is found that the longitudinal wind speed in the street depends linearly on the parallel component of the external wind velocity, while the recirculation (vortex) across the street depends linearly on the perpendicular component of the external wind velocity. In other words, velocities of longitudinal and vortex flow are linearly correlated with parallel and perpendicular components of external wind flow, respectively [43]. According to Dobre et al. [57], this phenomena occurs at a short distance form an intersection of a nonideal geometry street. Air flows in street canyons have been modeled analytically for any wind blowing angle with respect to the axis of the streets [58]. Results obtained using a theoretical model indicated good agreement with predictions from a detailed numerical solution of Reynolds-averaged Navier–Stokes equations. Specifically, it is found that helicoidal flow occurs only in sufficiently long streets with angled wind flows relative to the axis of the streets. On the other hand, Huang et al. [59] considered perpendicular wind flows on street canyons with various inclination angles and different heights of leeward and windward sides of the streets. In general, the results from their model show that the main factors that increase street ventilation include increased external wind flows, leeward side higher compared with the windward side, reduced height of the streets, and inflow wind direction.

Street intersections are also important parts of the urban areas. Indeed, street intersections can develop lateral eddies and create low pressure zones [44]. Specifically, several studies reported that street intersections have large role in flow distributions and in exchanges between canopy flow and atmosphere [46]. Horizontal corner vortices form near the end or the beginning of the intersecting streets [53]. A simplified operational model able to compute the flows in streets and exchanges with overlaying atmosphere has been developed by Soulhac et al. [46]. This model assumes that two transport mechanisms, associated with mass exchanges in horizontal planes and vertical air motions, are independent. This operational model has been developed for orthogonal intersections of two identical street canyons. The analysis results using this model indicate in the case of parallel flow along one of the intersecting streets, that the influence of the intersection on the flow of the perpendicular street can extend to a distance ranging from 1.4 and 2.2 of the street heights from the center of the intersection. In addition, when wind flows in an angle (not equal 0) with the intersection, some of the momentum of the flow along the main street moves to the cross streets [46]. The model also shows that the average wind speed along an infinite street for angled wind flows can be estimated by the average speed along that street when wind is blowing parallel to the street axis multiplied by the cosine of the incident angle.

However, some studies analyzed energy consumption of buildings in urban areas assuming that air flow in street canyons is fully mixed due to formation of vortices [36]. In particular, Wang et al. [60] have assumed that flow in canopy layer can be neutrally stratified for medium and strong wind flows due to the mixing induced by buildings. This assumption may not be accurate for weak background wind speeds as the atmospheric stratification becomes more important. Furthermore, most of the mesoscale models estimate mechanical drag coefficients for complex urban environments in order to determine surface wind speeds [61]. It is reported that the drag coefficients in urban areas depend on building plan-area fraction and can be estimated using CFD-RANS simulation with buildings modeled as staggered array of cubes for the case of New York City. Using this analysis approach, an increase in air temperatures is observed due to a reduction in urban ventilation resulting from an increase in mechanical drag coefficient.

3.5 Impact of Photovoltaic Deployment. Some reported UHI related studies have focused on the impacts of photovoltaic (PV) deployment on urban environments. For instance, Taha [62] evaluated and quantified the changes in outdoor air temperatures that result from large-scale PV deployment in urban areas. His study used mesoscale and meso-urban metrological models for the city of Los Angeles, California. In the study, only simple radiative balance is considered for various surfaces including those of buildings, streets, and PV panels. An effective albedo is used for the PV panels. This effective albedo depends on the reflectivity and the efficiency of the solar panels. The effective albedo is used in the simulation tool by replacing existing surfaces with PV panels. The reported analysis considered various scenarios of PV deployment levels, PV solar conversion efficiencies, and city albedo values. The results of the analysis indicate that deployment of PV panels does not generally have negative effects on outdoor air temperatures. In contrast, large PV deployments can cool down the outdoor air temperatures by about 0.2 °C. The analysis showed that, in the case of high density of PV deployment—with low PV conversion efficiency of 10%—for a hypothetical future cool city with high reflectivity roofs and pavement surfaces, warming of less than 0.1 °C can occur. In addition, Cortes et al. [63] used CFD analysis coupled with weather forecasting model and one-dimensional heat conduction solution to estimate the effects of PV panels on urban thermal environment in Osaka city, Japan. The analysis includes two cases: the first case is without any PV system while the second case involves PV panels covering the entire building walls and roofs with a 60 mm gap. The analysis results indicated that PV panels have some cooling effects for the building surfaces by preventing heat gains from solar radiation. The cooling effects are higher on the roofs during the day but higher on the walls during the night. The study also found that PV panels have cooling effects on the outdoor air temperature with an average reduction of 0.1 °C and a maximum reduction of 0.4 °C. Furthermore, Masson et al. [64] included energetics of the buildings and solar panels production as well as the interactions with roof surfaces in TEB scheme to study the impacts of solar panels on UHI effects. The study indicates that energy, water, and momentum exchanges within cities can be simulated using TEB with a resolution of urban blocks. In the analysis, both PV panels and thermal solar panels are considered to model an urban center within the city of Paris, France. The analysis found that during summer days, 0.2 K reduction in outdoor air temperature can be achieved by adding solar panels while an increase of up to 0.3 K occurs during nights. It is estimated that 12% reduction in air conditioning energy consumption can be achieved by installing solar panels. During winter months, maximum outside air temperatures can be reduced by up to 0.1 K and about 3% increase in domestic heating energy consumption.

Tian et al. [65] estimated the effects of building-integrated PV (BIPV) on microclimate of urban canopy layer for Tianjin, China using a model encompassing four sub-models. These sub-models consist of a PV thermal model, a PV electrical performance model, a building energy model, and an urban canyon energy model. The analysis results based on the developed model indicate that if PV panels are integrated with the building envelope, surface temperatures for the roof and the walls can be reduced by up to 9.4 °C and 4.6 °C, respectively compared with the case with concrete surfaces with 0.1 albedo. However, changes in canyon air temperatures before and after installing PV panels are negligible [65]. Furthermore, the study shows that, if the efficiency of the PV is increased from 5% to 50%, a maximum of 1.1 °C reduction in canyon air temperature can be achieved.

By coupling different tools, Lobaccaro et al. [66] evaluated the best areas on the building facades within urban areas for installing solar systems considering factors such reflection, albedo, and shading from the neighboring buildings. Specifically, the simulation tool "Daysim" is coupled with Rhynoceros and grasshopper modeling software in their study. One of the findings of their analysis is that the PV panels need to selected based on the highest contribution from the solar radiation components including direct, indirect, and defuse [66].

4 Overview of Urban Heat Island Modeling Techniques

Four objectives are generally considered when modeling and evaluating UHI effects including: improving energy efficiency, enhancing outdoor air quality, mitigating urban temperatures, and reducing detrimental health impacts [12]. Studies related to the UHI phenomenon can be classified into different categories depending on the analysis technique, data set, and scale used [12]. Recently, Hamdi et al. reviewed the state-of-art techniques for modeling and observing the urban climate change [67]. They indicated that thermal and dynamical parameterization is required for accurately modeling urban climate change to consider water and energy exchanges between urban surfaces with the surrounding atmosphere. Three categories of urban parameterization models can be considered including those related to the roughness and displacement heights for the air movement due to urbanization [67]. The other categories include one-layer urban canopy models (UCMs) and multilayer urban canopy models. Figure 2 summarizes the UHI modeling approaches reported in the literature including the scale level and the analysis methodology. Sections 4.1–4.3 outline the main features of various analysis approaches considered in the literature.

4.1 Analysis Scales. Reported studies can be classified based on the scale of the model resolution and associated analysis results as briefly outlined in this section.

4.1.1 Microscale Analysis Approach. Microscale analysis methods have spacial resolution from 1 to 10 m and temporal resolution from seconds to hours depending on the governing equations of the model used to evaluate the urban area [12]. Thus, microscale models can include more details about the UHI within the canopy and can investigate the interactions between buildings and their surrounding such as microclimate conditions, short and long wave solar radiations, shading from structures, as well as thermal effects of pavements and other surfaces, streets, plants, and others. In other words, microscale methods can represent the buildings' geometric features explicitly, model solar radiation exchanges between urban surfaces, and estimate the effects of urban morphology on the microclimate within urban canyons [41].

4.1.2 Mesoscale Analysis Approach. Mesoscale or city-scale models have spacial resolution between 1 and 10 km and time resolution of minutes [12]. Mesoscale models can be based on observations or simulation results using fluid dynamic equations integrated with radiation, cloud, and soil models applied on coarse cells [68]. Typically, buildings are considered as aerodynamic objects for the mesoscale models. In particular, the UHI effects related to factors such as anthropogenic heat release, building volume per area, and land coverage level are considered in vertical resolution from 0.2 to 2 km depending on the depth of planetary boundary layer [12,68]. Based on a description by Gros et al. [41], buildings are represented implicitly not explicitly where physical parameters are defined by urban fabric characterization to predict the atmosphere above the urban area.

Ichinose et al. perform a mesoscale-based analysis to determine the impacts of the anthropogenic heat on the urban climate in Tokyo, Japan, [69]. Specifically, they used a numerical simulation model based on the Colorado State University Mesoscale Model [70]. In their study, the urban canopy layer has been neglected but the impact of the sea breeze on the urban climate change was considered. The study found that decreasing water heating consumption to 50% and reducing air-cooling consumption by 100% would have low impact (around 0.5 °C) in mitigating the UHI temperature. In addition, the study indicated that UHI forms due to weakness of sea breeze during the winter in Tokyo. During the summer, the impact of solar radiation on urban climate change is found to be more dominant than the anthropogenic heat.

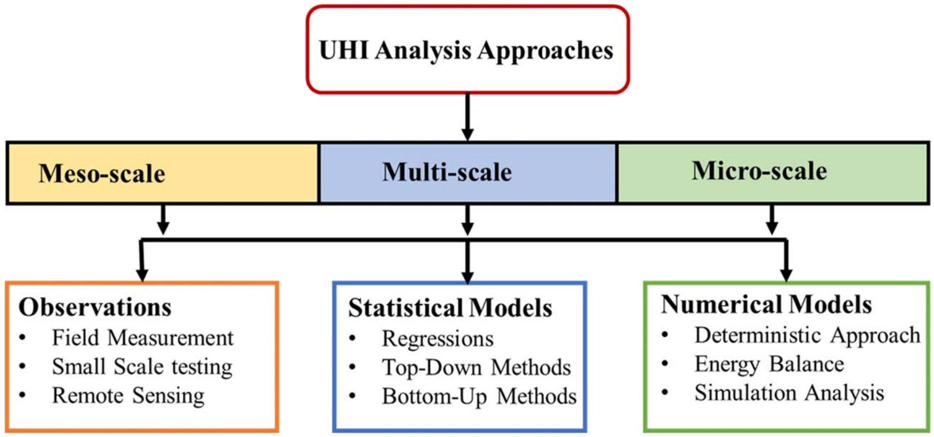

Fig. 2 Summary of UHI modeling techniques based on scale levels and analysis methods

In 2000, Masson developed a mesoscale model for urban atmosphere using an energy balance based model referred to as Town Energy Budget (TEB) [71]. Basically, the model represents the urban area by parameterization of three main surfaces including roofs, walls and roads. An explicit energy budget is considered for each surface in addition to energy budgets set for snow on roofs and/or roads. The model divides the area into a meshed grid. The grid meshing scheme can be different for various land types such as inland water, sea, and city buildings/roads. Heat fluxes including latent and sensible; radiative; and momentum fluxes can be estimated for each grid and used as boundary conditions of the mesoscale atmosphere model. However, all buildings in this model are assumed to have identical height and width. The roads are assumed to be long and identical using the canyon hypothesis. These simplifications make the model predictions slightly overestimating the trapped solar radiation compared with the case of crossing urban canyons. However, Masson highlighted the importance of coupling the anthropogenic model to an aerosol radiative active atmosphere and urban surface scheme for accurate evaluation of urban climatology. The model provides a substantial improvement to the previous mesoscale models that mostly consider the urban areas as flat surfaces with different thermal and dynamical properties (i.e., roughness, thermal capacity, and thermal conductivity) that those of the soil medium. Kusaka and his team developed a single-layer mesoscale model which is similar to TEB but considers different urban canyon orientations and solar azimuth angles for solar radiation calculations [72]. They compared the predictions of their single-layer model with those obtained from a more detailed multilayer model for a city with a canyon aspect ratio of 2/3. They found that their single-layer model has a good agreement with the multilayer model with the total energy budgets estimated by the two models are found to be close. Martilli and his team also developed an urban parameterization mesoscale model [33], and evaluated its predictions with and without coupling it with a building energy model developed by Salamanca et al. [73] Salamanca and Martilli [74]. This building energy model acccounts for heat transmissionsthrough building envelope, natural ventilation effects, internal heat gains, HVAC energy demands, and internal radiation exchanges to allow a more accurate representation of the thermal interactions between the building and surrounding atmosphere. The three UCMs developed by Kusaka et al. [72], Martilli et al. [33], and Salamanca et al. [73] have been implemented in the WRF simulation environment which is commonly used for a wide range of studies worldwide [75]. The prediction accuracy of these UCMs has been thoroughly validated [76] not only for mesoscale urban meteorological analyses but also for climate change evaluations [77].

4.1.3 Multi-Scale Analysis Approach. To generate more accurate results and develop a more comprehensive analysis of UHI effects, multi-scale approach is recommended to integrate different models that have different scales [68]. For instance, coupling mesoscale with microscale models would reflect more realistic results and allow for investigating the interactions between buildings and their surroundings. Masson reviewed the main urban canopy energy balance models that could be coupled with mesoscale urban atmospheric models [78]. Based on his review, three classes of urban surface modeling can be considered including empirical models, modified vegetation models, and urban surface energy balance models. The last two categories of models could be with or without consideration of drag in the urban canopy. Masson also discussed the advantages and disadvantages as well as applications for each modeling category [78]. For example, empirical models are suited for cases with well understood observations. Modified vegetation models are applicable for large-scale global climate analyses while the urban surface models are suitable for regional climates where detailed interactions between the urban components are considered

However, this approach has its own challenges. Based on a review by Mirzaei [68] there is gap of knowledge for multi-scale analysis approach that requires more research to develop more efficient models. This gap is a result of the fact that building microclimate models have higher resolution, but they cannot extend to cover the entire space of a city because of the computational cost and complexity to predict important parameters. On the other hand, mesoscale models can be extended to large cities, but they have lower resolution in providing details about urban canopy layer. For instance, the unmatched spatial and/or temporal resolutions of different models as in the case of atmospheric and canopy turbulence with each model has different temporal and spatial scale causing significant computational challenges [12]. Chen et al. [79] did perform a multi-scale assessment for reducing heat-related mortality from urban vegetation coverage. The study has been conducted for Melbourne Central Business District, Australia. The study couples three models including a mesoscale model, an urban canopy model, and a building energy model. It uses the mesoscale model to quantify the effects of ten different vegetation schemes on the local climate. The building energy model is used to simulate indoor thermal performance of five residential buildings using the results of the mesoscale model. Then, the study estimated the potential reduction in heat related mortality based on correlation between simulated indoor mean daily temperature and 20 years record of daily mortality rate. Another study that considered both mesoscale and microscale urban meteorological is that reported by Ohashi et al. [15] to simulate the outdoor heat stress and heat disorder risk in Tokyo.

4.2 Analysis Techniques. The reported studies can be classified based on the analysis technique followed to achieve the purpose of the study as outlined in Secs. 4.2.1–4.2.3.

4.2.1 Observation-Based Approaches. The observation-based approaches include small scale, field measurement, and thermal remote sensing data [12]. Small-scale approach relies on observed results from wind tunnels or water channels using small-scale models of urban centers or areas. Usually, this type of approach is used to study flow patterns within or above urban areas. In the field measurement approach, sensors are used to observe the weather within the urban areas. Based on the field data, researchers could estimate the impact of some factors enrolled in UHI formation. The main disadvantage of field measurement approach consists of the high cost and time required to conduct the measurements. The thermal remote sensing approach utilizes thermal images taken from planes or satellites to predict air temperatures from surface temperatures as well as to estimate the impacts of some factors such as surface material, albedo, and vegetation level on the urban air temperatures. For instance, among five physical characteristics that are albedo, sky view factor, and percentages of impervious surface, green space, and water. The observational models are mostly used in the early stages of urban climate studies [7]. However, Klok et al. [80] found that green space, impervious surface, and albedo are in order the most significant characteristics that affect SHI. The analysis results show that 69% of the variance in urban air temperature is explained by green space where a reduction of 1.3 °C in surface temperature could be achieved by a 10% increase in the green space. In addition, the study indicated that urban air temperatures or UHI values can be estimated from urban surface temperatures or SHI values estimated using thermal remote sensing approach through sets of complicated correlations. Based on Coseo and Larsen [23], among 14 variables, impervious surface and tree canopy were determined to be the most effective physical characteristics that explain nighttime temperature differences and are responsible for 68% of the variance in outdoor air temperatures at 2 am. The same study found that 0.74 °C (0.62 °C during a heat event) increase in outdoor air temperatures can result by a 10% increase in impervious surface while a 10% increase in tree canopy can lead to 0.2 °C (0.35 °C during a heat event) reduction in outdoor air temperatures.

4.2.2 Numerical Modeling Approaches. These approaches utilize mathematical and deterministic models of urban areas. Based on the review of Mirzaei and Haghighat [12], the most reliable numerical modeling approaches are based on energy balance and dynamic numerical solution techniques. In addition to the solution techniques, the effectivness and the accuracy of the numerical modeling approaches depend on the required computational power. Indeed, the comutational cost is one of the main disadvantages of the numerical modeling based approaches and depends on the number of control volumes (number of nodes) that cover a part or the entire domain of the considered city. Numerical modeling based approaches are often considered the most reliable methods for UHI analysis [12]. Mesoscale models are usually considered when an overall evaluation of the UHI factors over a city scale is considered. For these models, no details of the weather within specific street canyon or individual based details about building operations and heat emissions are considered. On the other hand, many studies focused on the microclimate of the urban area since it has direct impacts and interactions with buildings' energy consumption and outdoor thermal comfort levels in addition to its role in determining the UHI effects and/or mitigation strategies. In the reported literature, the models utilized to predict ambient air temperatures are based on four model categories including climatology models; empirical models; computational fluid dynamics; and models using statistical regressions, probability, or artificial neural networks methods [17]. In the near future, the estimation of the effects of proposed designs on urban thermal environment would be required by developers and architectural designers at the planning and design stages [81].

However, it has been noticed that several of the developed models usually are not linked and they have been developed based on specific needs and research focus areas. Due to the large number of factors that contribute to the UHI formation and the associated computational costs and resolution scales, most of the developed models have limited scope based on specific objectives. Thus, some reported models consider few UHI factors without including their interactions with other factors. For example, high-rise buildings and narrow streets could cause shading that reduces the surface and outdoor air temperatures, but they also reduce wind speeds within the urban area which can lead to a reduction in air ventilation and thus to an increase in UHI effects. In addition, high-rise buildings require more energy consumption and result in more anthropogenic heat release within the urban area, potentially increasing the UHI effects. Therefore, it is better to consider the integrations between all influencing factors to have a more realistic model of the urban environment. No comprehensive model or tool is available to simulate UHI phenomenon considering all the possible contributing factors. Duarte et al. [5] states that, to perform a comprehensive microclimate analysis, a wide range of numerical models including aerodynamics, thermodynamics, and radiation exchanges should be considered. Some studies indicate that if the urban density considers the neighborhood typology and other relevant parameters such as type of materials, characteristics of residents, historical, social, and cultural contexts in addition to the geometry, then the relation between urban form and the energy performance can be complex and more unique for each urban center [82]. Furthermore, Targhi and Van Dessel [83] recommended that UHI should be investigated and studied for each location independently. There are several attempts to integrate many different tools and models of to have a more comprehensive representation and realistic results of UHI phenomenon. It is not only the models' integration is important but also the manner for this integration can affect the analysis results. In real situation, the integration between UHI factors is reciprocal, dynamic, and interactive (i.e., each model depends on other models). Nevertheless, because of the simulation challenges, some studies consider limited set of interactions to evaluate the impact of some factors but not others. Huber and Nytsch-Geusen [84] mentioned some advantages and disadvantages of coupling different tools. Based on their study, one of the benefits of coupling different tools is that the computation time can be reduced significantly if those tools are executed in parallel using different cores; On the other hand, coupling tools can lead to some challenges. In particular, data transfer between models is often one of the main challenges [84]. Some approaches to reduce simulation time include reduction of thermal zones, simplification of building envelope details, and use of parallel simulation techniques [85]. Reinhart and Cerezo Davila [86] discuss the workflow and the implementation procedure of bottom-up based urban building energy models. According to their analysis, the simplest implementation approach consists of using steady-state heat balance model for each building type to scale up the results to the entire building stock by either multiplying by the number of buildings or by a floor area-weighted function. The authors state pointedly that this type of modeling approach ignores the shading impacts, local wind patterns, and other effects of urban morphology that can significantly influence the energy performance of buildings. Moreover, steady-state methods only predict building heating loads adequately. To estimate accurately building cooling loads, dynamic thermal simulation tools such as EnergyPlus, TRNSYS, and DOE-2 are generally recommended [86].

4.2.3 Statistical Approaches. The use of statistical analysis methods including regression analyses is another set of approaches considered to evaluate the impact of various parameters on desired output such as the UHI intensity and urban density, as described by Kavgic et al. [87]:

- *Top-down method:* Top-down approach relies on the use of top-level input variables like energy price, macroeconomic, and climate indicators to derive and predict desired output variables such as energy consumption of building stocks [31]. In addition, the top-down methods are based on regression analyses of historical data to derive models and correlations to predict desired output variables. These methods are generally unable to analyze the impact of new technologies and interactions [88]. Observation-based approaches are usually considered as types of top-down analysis methods.

- *Bottom-up method:* Based on the description provided by Reinhart et al. [88], the bottom-up analysis approach uses a set of models for building performance. These models, once calibrated based on measured data, can be utilized to determine the effects of various measures and strategies on the performance of buildings as surrounding areas. Using building stock modeling approaches, predictions from the set of building models can be extrapolated to larger scales to determine for instance the energy consumption of an entire urban area [31,88]. Most of the simulation approaches are considered part of bottom-up analysis methods.

4.3 Modeling Methodologies of Urban Heat Island Effects. The potential UHI effects in urban areas have been widely evaluated in the literature. In this section, the reported modeling methods for three major UHI effects are discussed including outdoor thermal comfort, building energy performance, and access to solar radiation.

4.3.1 Energy Performance of Buildings. As previously mentioned, buildings are major parts of the UHI formation. Buildings consume energy to meet operational requirements including comfortable indoor environments for occupants. However, buildings can affect microclimate weather due to waste heat from air conditioning, ventilation, and infiltration, heat transfer through the envelope, stored solar energy within the envelope, and shading effects on street canyons as well as surrounding buildings. Other types of heat waste may exist in industrial facilities such as factories and power plants. UHI can affect building energy consumption positively if it occurs during winter periods in cold locations (i.e., where heating load is dominant most of the year) or negatively if it occurs during summer periods in hot locations (i.e., where cooling load is dominant throughout the year). There are two-way interactions between building energy consumption and microclimate weather. In general, current building energy simulation practices mostly neglect UHI effects [22]. Several studies analyzed the energy consumption measured for single urban buildings using weather data taken from rural weather stations [89–94]. Although standalone detailed building simulation tools allow to predict building energy performance under various operation conditions and can be applied to evaluate cost effective energy efficiency measures for new and existing buildings, they do not permit to assess the interactive effects of urban microclimate and building energy systems. For instance, as the outdoor air temperatures increase, the need for space cooling inside the building increases to maintain the desired level of indoor thermal comfort. However, air-based cooling systems often reject heat to the outdoor environment resulting in an increase in outdoor air temperatures and subsequently building cooling loads.

Limited analyses have been reported to investigate the mutual thermal interactions between buildings and their surrounding urban environment. For instance, Kikegawa and his team developed a one-dimensional numerical simulation tool to investigate the UHI effects on the building's cooling demands [95]. The model consists of modules including a mesoscale module for the canopy layer, a microscale module for the urban canopy layer, and a module for building energy consumption. They verified their model against observation data obtained for the Ootemachi district in Tokyo, Japan. The modules for the urban canopy layer and the building energy consumption interact with a two-way directional coupling, but the thermal interactions between urban canopy layer and the mesoscale layer are modeled through one directional coupling. Thus, the mesoscale layer can impact the urban canopy layer but not the other way around, affecting the accuracy of the model predictions. The analysis results indicated that eliminating heat released from air-based cooling systems could reduce the canopy air temperature by 1 °C during the summer in the Ootemachi district. In addition, the study indicated that 1 °C drop in urban canopy temperature could save up to 6% of the energy demand by air-cooling systems.

Another reported study developed a model, referred to as the revised Architectural-Urban-Soil-Simultaneous Simulation Model by Tanimoto et al. [96]. This model is made up of three sub-models specific to urban atmosphere, land surface, and building thermal performance. These sub-models are coupled dynamically. Urban atmosphere sub-model consists of equations of momentum as well as vapor and heat transfer within the urban canopy. The sub-model is multi-layered with only vertical atmospheric diffusion is considered. For the soil sub-model, one-dimensional heat conductive equation is used for three types of land cover (bared soil, lawn, and pavement). The estimation of building thermal loads, exhaustive heat corresponding to HVAC systems and solar radiation exchanges are considered in the third sub-model (i.e., building thermal performance sub-model). In this third sub-model, 12 factors including building volume, HVAC operation schedule, window glazing area, rooftop finishing, reflectance of solar radiation, and ground surface covering are considered to investigate their effects on UHI level. Similarly, Bueno et al. [16] developed an analysis tool that couples an urban canopy model with a building energy model. Specifically, a modified TEB model and EnergyPlus were coupled to estimate building energy consumption, building facade temperatures, and urban canyon air temperatures. The building model has specific geometric dimensions with a square shape and a height of 20 m with identical surrounding buildings. In the tool, the mutual interactions between the two models are achieved through exchanging input/output data [16]. First, TEB calculates wall and roof temperatures and canyon climatic conditions. These data are then set as boundary conditions for Energy Plus model. HVAC waste heat fluxes and window temperatures are then calculated and used in a new iteration for the TEB model. This procedure is repeated until convergence of temperatures within 0.05 °C is achieved. In addition, a validation analysis of the coupled scheme is carried out by comparing the results with field measurements in Toulouse, France. However, this approach is not suitable for coupling with atmospheric models due the number of required iterations [97]. In addition, it is important to note that, in case of using existing building simulation tools as in the case of this tool, a calibration for the building model is required to ensure that the model reflecting the actual building thermal performance before studying the effect of different strategies and operation alternatives. Based on the reported results, the building model predictions did not match measured data and adjustments were made so the predictions are close to the measured data. Furthermore, the internal loads of the building are considered constant throughout the day. Using schedules for different internal loads would provide more realistic building operations and diurnal consumption profiles. Using the developed tool, the study found that shading devices are very effective in mitigating UHI effects and reducing the cooling energy consumption of buildings [16]. Moreover, heat recovery systems are found to reduce heating energy consumption. On the other hand, the study found that, using economizers for HVAC systems are not effective to reduce building energy use and to mitigate UHI effects.

Another model that is based on RC thermal network modeling of urban canopy microclimate and building energy performance has been developed by Bueno et al. [36] to model the interactions between urban climate and energy performance of the buildings. Buildings with single zone and urban canyons with well-mixed air are assumed in the model. Single thermal zone models are assumed to be sufficient to predict the energy performance of low to medium rise buildings. The reported results from the study showed that the developed model is able to predict urban temperature variations compared with coupled scheme between the detailed EnergyPlus simulation tool and city's energy balance [16]. Bueno et al.'s study indicated that infiltration and natural ventilation are the main mechanisms by which the UHI affects the indoor energy performance of the buildings [36]. Thus, commercial buildings are affected by UHI mostly through natural ventilation or HVAC economizers. On the other hand, the study showed that waste heat emissions from HVAC systems and the exfiltration are the main mechanisms of buildings affecting UHI. However, it will be useful to consider the impacts of high-rise buildings common in urban centers as well as on building-integrated PV systems on UHI effects.

Another attempt to model the mutual thermal interactions between buildings and urban microclimate is reported by Bueno et al. [97]. In this study, a building energy model has been developed and integrated in the urban canopy model TEB. The study found that, comparing with the approach in Ref. [16], TEB overestimates the solar radiation reaching building facades. TEB capability has been improved to more accurately estimate building heating and cooling demands when compared with predictions from EnergyPlus [31]. The accuracy of TEB results is reported to be within 5 and 3 kWh/m^2/year for heating and cooling demands, respectively. The study showed that, not estimating the road surface temperatures explicitly may underestimate the cooling demands by up to 18% in the case of isolated buildings with low levels of insulation. Weather data are usually collected from rural areas and airport stations that are usually in open spaces further away from urban areas. Therefore, these weather data usually do not reflect the ambient air temperatures or wind speeds occurring in urban canyon streets and in urban areas. Some studies focused on adjusting weather data to account for the UHI phenomenon. One of the recent attempts was by Bueno et al. [22], where a weather generator is developed to consider the UHI phenomena from both components of the UHI effects: the aggregate effect of the city on urban boundary layer (mesoscale), and the urban canyon effect (microscale). The model is developed to be computationally fast to predict the UHI effects in a city with an expected error of about 1K. Based on a comparative analysis with field data, the study found that both components (mesoscale and microscale) need to be considered in computing the UHI effects. In addition, the study found that horizontal building density and vertical-to-horizontal urban ratio are the most critical morphological parameters that affect the accuracy of the results. However, the developers of the urban weather generator (UWG) stated that their model is not appropriate for heterogeneous area, or a city area surrounded by urbanization or close to large water bodies.

Gros et al. [98] developed a tool called EnviBatE to combine building energy modeling with urban canopy modeling. In this tool, building energy and microclimate models have been coupled to investigate the impact of cool materials on both building energy consumption and the surrounding atmosphere. Simplified weighting factor method has been used in this tool to compute the thermal response of buildings. A 3D finite element solver, GMSH, has been used to generate main mesh for two domains (building and urban canopy). Each domain is divided into cells that are interfaced through urban surfaces. Energy balance is used to find the outside surfaces temperatures. These surface temperatures as well as ambient air temperatures and building heating/cooling loads are computed simultaneously. The study found that cool paints are very effective in reducing surface temperatures. The authors stated that 78% of cooling energy demands can be reduced by using cool paints.

Another urban simulation environment, referred to as urban modeling interface, has been developed [88]. UMI uses three existing tools including Rhinoceros CAD modeling, EnergyPlus, and Daysim. The coupling of these tools forms an integrated urban simulation environment that can be used to analyze operational energy, daylighting, walkability, and outdoor thermal comfort of urban areas. Daysim program combines the Perez SKY model (in order to simulate solar irradiances temporally), a backward ray-tracing algorithm, and a daylight coefficient approach [26]. Daysim is commonly used for daylighting analysis especially for large commercial buildings [88]. UWG has been used in this simulation environment to develop a specific weather file for the modeled urban area [88]. However, the urban weather generator is not in reciprocal interaction with the building energy model. Moreover, the thermal comfort model considers only the effects of ambient air temperatures and direct solar radiations. Mean radiant temperatures and local wind effects are not considered. One of the benefits of the simulation tool is transferring data from Geographic Information System (GIS) to CAD which makes it easy to model an existing building [88]. Data provided by GIS includes building's height and footprint area, window to wall ratios, age of the building, building function, shading systems, and occupancy type among the parameters needed to model the building thermal performance [99]. UWG also has been coupled with UMI to study, for neighborhoods, the relationships between building energy performance and complex urban form [82]. In particular, the building function can impact the thermal interactions between building energy consumption and urban form. Specifically, increasing urban density is found to increase building energy consumption for case of residential neighborhoods, while building energy consumption for commercial neighborhoods can be reduced if the urban density is increased. Again, no dynamic and reciprocal integrations between the buildings and microclimate were considered in the analysis.

Some studies have focused on estimating the average impact level of urban areas. In particular, Rodriguez-Alvarez [100] has developed a tool called Energy Index for Buildings (UEIB) to assess energy performance of the buildings in urban areas. The model uses the average build-up area with uniform distribution and averaged building height to present an existing urban area. This tool considers mostly the impact of urban morphology on the energy consumption of buildings using average performance indicators. Other similar tools can be used especially for urban areas smaller than 20 hectares [100].

Other studies have evaluated the impacts of urban weather on the energy consumption by building air conditioning systems. For example, CFD tool (OPENFOAM) combined with building energy simulation tool (EnergyPlus) have been used to find microclimate temperatures and heat fluxes on building surfaces [101]. Uniform neighborhoods with different densities have been considered in this study. The reported results from the study indicate that the microclimate in urban areas can reduce the coefficient of performance (COP) of building air conditioning systems by about 17%. OPENFOAM and EnergyPlus runs in parallel with hourly data exchanges transferred from EnergyPlus to OPENFOAM. The analysis reported in the study only considers 1 day (i.e., design day) and the ground cover is assumed to be grass. The main goal of the analysis is to evaluate the impact of neighborhoods on the COP changes of the cooling systems installed near the windward side, leeward side, and rooftop of the building. In the analysis approach, EnergyPlus provides surface temperatures to the CFD tool that calculates the air temperatures used in estimating the effective COP value to assess changes in the energy performance of cooling systems. The study found that, for high-density neighborhoods, leeward side is the preferable location to install the cooling system to achieve the lowest impact on the COP while for low density neighborhood, both leeward and windward sides are recommended [101]. However, the analysis did not investigate the impact of urban microclimate on building total energy consumption.

Spatiotemporal variability of energy consumption for different existing urban centers has been estimated through integration of statistical and analytical bottom-up models [99]. A simplified building thermal model suitable for one conditioned zone above ground level and one unheated basement is considered in this model. The annual energy consumption of each building is calculated based on statistical data and building class category obtained from GIS. Based on this study, the proposed approach has a percentage of error ranging from 4% to 66% for energy services of single building scale due to the limitations in estimating the temperature set points and ventilation and infiltration rates. The percentage of error decrease if the model is used on the whole district zone (between 1% and 19%) with the use of statistical and analytical methods as well as statistical zoning techniques [99]. However, solar radiation impacts on building energy performance including and shading effect are not included in this study.

One reported study has focused on citywide energy consumption using available detailed statistical data such as GIS [85]. In this study, urban building energy modeling is mainly considered to estimate energy consumed by buildings within urban districts using GIS datasets and UMI tool. The study found that, for the summer months, commercial buildings are responsible for more than half of the energy demand during working hours while residential sector is responsible for about third of the energy demand during the afternoon periods. For the winter months, the study states that, energy demand at nights and early mornings are higher due space heating. Moreover, two scenarios of reducing energy demand of buildings were considered in the analysis. One scenario consists of adding PV on 50% of the available roof areas. The other scenario involves the increase of temperature set points for the commercial buildings between 5 pm and 6 pm to reduce their cooling loads. The analysis results indicate that the peak electrical demand is reduced more significantly for the second scenario estimated to be doubled than that obtained for the first scenario of deploying rooftop PV systems. The model used in the analysis does not consider the mutual interactions between buildings and their surrounding microclimate [85].

SUNtool is developed to help urban designers to optimize their designs in terms of environmentally sustainability [102]. This tool integrates microclimate, thermal, stochastic occupancy, and plant sub-models. However, SUNtool does not include thermal modeling of the microclimate and energy exchange between buildings. It has been indicated that economic and cost-benefit analyses for energy efficiency measures and environmental cost are not included in such models [102].

4.3.2 Outdoor Thermal Comfort. Outdoor thermal comfort is one of the important criteria that need to be considered when designing urban centers. Several studies have investigated factors that enhance human thermal comfort in outdoor environments. For example, Duarte et al. [5] evaluated the impact of vegetation on urban microclimate in subtropical climate. ENVI-met has been used in this evaluation analysis for various vegetation distribution configurations including central parks, pocket parks, and street trees. A series of parametric analyses is conducted considering high-density urban blocks with different greening distributions. Based on the analysis results, it is found that vegetation can reduce UHI mostly during the daytime. Moreover, it is found that street trees are more effective to reduce urban ambient air temperatures compared with highly build-up urban centers. In addition, a reduction of mean radiant temperatures is found to be highly effective in improving outdoor thermal comfort levels especially for central parks. Another analysis found that for highly dense urban areas, adequate urban geometric configurations area can mitigate the swing in mean radiant temperatures and improve the outdoor thermal comfort [14]. A study that considered both mesoscale and microscale urban meteorological is conducted by Ohashi et al. [15]. This study evaluated the outdoor heat stress and heat disorder risk in Tokyo using urban HDR simulation developed by Ohashi et al. [103]. The analysis is based on a mesoscale atmospheric model, an urban canopy model, and a building energy model. However, the analysis results indicated that building greening did not decrease the outdoor wet bulb globe temperatures and heat disorder risks. In addition, it is found that high albedo surfaces have negative effects on heat disorder risks since they increase the wet bulb globe temperatures by an average of 0.6 °C and a maximum of 1.7 °C. The study also indicated that shading could reduce heat disorder risks significantly. The study also concluded that it is important to account for solar and infrared radiation in addition to air humidity and temperature to adequately estimate outdoor thermal comfort level [15].

ENVI-met, RayMan, and UMI simulation tools have been used by Targhi and Van Dessel [83] to assess and evaluate the impact of urban geometry and form on microclimate of open spaces for the case study of Worcester, Massachusetts. ENVI-met has been used to estimate the main microclimate parameters including wind speed, relative humidity, vapor pressure, air temperature, and mean radiant temperature. RayMna has been used to calculate sunshine duration, radiation flux, and shading areas as well as the physiologically equivalent temperature (PET) to assess outdoor thermal comfort. The study found that E-W canyon leads to more heat stress and less pedestrians thermal comfort, while N-S canyon provide better outdoor thermal comfort level from 8 am to 5 pm.

A 3D-CAD system has been used to develop thermal design tool for use in planning outdoor spaces including buildings, ground, and vegetation based on energy balance [81]. Analysis results using this microscale model found that trees can reduce surface temperatures from 50 °C to about the ambient air temperature of 32 °C with a reduction of about 10 °C in mean radiant temperature used as an indicator to evaluate outdoor thermal comfort.

Another study indicates that UHI is more noticeable during nighttime with urban air temperature increases during the night more than it does during the day [39]. ENVI-met has been used in the study to investigate seasonal variability of outdoor thermal comfort levels and air temperatures for Phoenix, AZ. This study shows that, in arid areas, factors such as shading on canyon streets from high-rise buildings, high thermal inertia, heat storage of urban surfaces, and high amount of vegetation may cause what is referred to as the cool island effect at least part of the daytime (i.e., early part of the day for the case of the study) resulting in better the thermal comfort. However, dense and compact streets reduce air ventilation rates and sky view factors, causing heat trap and increasing urban air temperatures especially from mid-afternoon to the evening and during nighttime [39]. It is found that mean radiant temperature is the most important meteorological parameter to determine outdoor air comfort and human thermal comfort during summer.

Taleghani et al. [104] evaluated outdoor thermal comfort levels for five urban forms in Netherlands. The study used ENVI-met, a CFD-based program combined with RayMan tool, to investigate the outdoor thermal comfort. Specifically, ENVI-met has been used to generate the main four parameters affecting outdoor thermal comfort including air temperature, mean radiant temperature, relative humidity, and wind speed. RayMan uses physiological equivalent temperature (PET) method to estimate the outdoor thermal comfort level using the four thermal comfort parameters generated by ENVI-met. The study has been conducted for the hottest day observed during one year with south-east prevailing wind direction. The study found that urban form mostly affects radiant temperature and wind speed of the urban canyon. Moreover, the analysis results indicated that courtyard could provide the highest thermal comfort hours (17 h) followed by linear north-south blocks with 8 h periods of outdoor thermal comfort.

4.3.3 Access to Solar Radiation. Solar radiation has a significant effect on the microclimate of urban areas. Indeed, shortwave radiation has a direct effect on various surfaces including walls, roofs, streets, and pavements and has indirect effect through heat solar gains to buildings resulting in heat release from the use of AC systems in hot areas. Different studies have investigated the impacts of solar radiation using different approaches and applications. In some of the reported analyses, buildings shapes and locations are determined to maximize the benefits of solar energy in urban areas [26]. In particular, the effects of different facades of the neighboring buildings are considered (green, glazed, concrete, and aluminum) [26]. It is found that the main parameters that influence solar radiation reaching the building include road pattern, building orientation, distribution of volumes, height of buildings height (with respect to each other), finishing materials, and width of urban canyon. Daysim program has been used to determine solar heat gain potential for building roofs and facades. The study found that annual solar radiation access on vertical surfaces increases up to 138% if the buildings covering ratio decreased from 100% to 25% (ratio between building's footprint and the area of the land). In addition, it is reported that reflected solar radiation by surrounding buildings can have significant effects as it can compensate for the shading losses if the solar reflectance of surrounding buildings is more than 60%. On the other hand, it is found that surfaces with high reflectance can cause overheating in urban areas and can increase the glare effects that result in reduced thermal comfort inside and outside the buildings. Furthermore, green facades are found to mitigate UHI effects while dark surfaces increase them while reducing solar radiation access to the buildings. The main challenge is to increase solar radiation especially on the buildings' roof for PV generation and to limit the impacts of solar heat gains on both buildings' energy consumption and urban air temperatures. Indeed, some factors that can increase the PV generation potential have negative effects on outdoor and indoor thermal comfort.

A simplified solar balance model has been developed by Bernabé et al. [25] and validated against SOLENE, a detailed solar simulation model. The simplified solar balance model is used to investigate the influence of urban morphology on solar radiation penetration to the buildings and their surroundings. It has been reported that a decrease in sky view factor reduces losses in long-wave radiation and turbulent heat transfer. Moreover, it is found that due to the complexity of urban morphology, effective averaged sky view factors can be used to explain variations in outdoor temperature.

A solar radiation model—referred to as r.sun—has been developed by Suri and Hofierka [105] to estimate the three components of solar radiation (beam, diffuse, and reflected) on urban surfaces (mainly roofs). The model has been fully integrated within the GRASS GIS simulation environment developed for ten European countries. The simulation environment has been used with a 3D city model implemented in GIS to assess the potential of PV in urban areas [99]. Using the case of a city in eastern Slovakia, the analysis found that two thirds of the city energy consumption can be generated by rooftop PV. However, the analysis did not consider the effects of rooftop PV on the microclimate within the urban canopy as well as on the energy performance of buildings. A simplified radiosity algorithm to account for the impacts of obstructions on the sky radiation and reflected radiation as well as to predict surfaces irradiance in urban areas has been developed by Robinson and Stone [106]. A comparative analysis has indicated that the developed algorithm is more accurate than isotropic sky and anisotropic sky models with comparable computational time.

5 Urban Heat Island Mitigation Measures

The reduction of the UHI effects has several benefits such as lowering energy demand from buildings during the summer periods, reduction in outdoor temperatures (preferred in hot summers), improvement in indoor and outdoor thermal comfort levels, decrease in maintenance requirements, and enhancement of healthy environments [83]. Based on various analysis and modeling approaches as outlined in this review, the performance of several UHI mitigation strategies has been assessed. Improving the designs of buildings and street canyons; increasing vegetation coverages; increasing the albedo of surfaces materials; and reducing anthropogenic heat emissions are among these UHI mitigation strategies [12]. A summary of the reported literature on common UHI mitigation measures is outlined in this section.

5.1 Vegetation and Trees. In particular, Chen et al. [79] found that 5–28% reduction in heat related mortality rate can be achieved if the vegetation coverage increased by 15–33%. Increased vegetation coverage is found to be an effective measure for reducing UHI in urban areas. Based on Chow and Brazel [107] xerophytic shade trees have a strong mitigation impact on UHI when compared with the effect of xeric residential areas with microscale near-surface temperatures can be reduced by up to 2.5 °C and 1.1 °C, respectively. The study found that nocturnal cooling effects are more significant than the diurnal effects. Some reported studies have focused on the impact of vegetation on the surface temperature variation as a strong indicator of ambient air temperature levels. In particular, a study of microscale model found that trees can reduce surface temperatures from 50 °C to about the ambient air temperatures of 32 °C [81]. Based on this study, a reduction of mean radiant temperatures of about 10 °C when can be obtained when tall trees are present. Furthermore, the study indicated that a significant reduction in Heat Island potential can be achieved when tall trees are used in residential blocks that were initially without any trees. Another study found a reduction of about 8.4 °C in surface temperatures underneath vegetated areas [108].

5.2 Urban Architecture. To assess the urban architecture impacts on UHI effects, Rajagopalan et al. [40] investigated different configurations for building shapes including reducing the height of high-rise buildings, adding off scale sky scrapers, and stepping up the building height levels on microclimate weather conditions of a tropical city in Malaysia. The study found that increasing the height of the buildings with narrowing the streets leads to an increase in the microclimate temperatures due to low wind speed in the street canyon. In addition, stepping up the building heights, with the upwind buildings are higher than the downwind buildings, was found by this study to be the most effective configuration to mitigate UHI as it leads to even distribution of wind speed that increases the overall natural ventilation of the considered urban area.

5.3 Roof Treatments. Scherba et al. [109] compared the heat island impact of commercial building roofs including black roofs, white roofs, green roofs, and PV-covered roofs in six US cities. Based on the study, white-PV roofs can save about 40% of peak flux and 55% of total flux compared with unshaded black roofs. Moreover, green-PV roofs can save about 45% and 42% of peak and total fluxes, respectively. However, the study shows that adding PV on black roofs has negligible effect on the peak flux while the total flux is reduced by about 11%. Meanwhile, adding PV panels on white or green roofs increases the sensible flux. However, the study did not address how these fluxes affect the urban local climate considering the effects of other surrounding buildings. Gros et al. [98] investigates the impacts of cool materials on both building energy consumption and its surrounding ambient environment. Based on this study, cool paint is efficient as it decreases the absorbed solar irradiation by the urban surfaces when increasing the reflectance from 0.3 to 0.9. The authors stated that 78% of cooling energy demand can be reduced by using cool paint. In addition, in case of urban centers with low building density and high latitude locations, cool paint is found to be more effective on vertical walls than roofs in terms of reducing the microclimate temperatures. Using cool surface pavements like permeable asphalt pavements, pervious cast concrete pavements, porous concrete pavements, and interlocking concrete pavements could also be used to mitigate UHI [5].

6 Summary and Conclusions

The review analysis summarized in this paper clearly indicate that there are significant research gaps in accurately modeling UHI effects and consequently assessing the best mitigation strategies to improve the energy performance of urban built environment. Some of the main findings and recommendations for future UHI related studies include the following:

- Modeling the interactions between different factors of UHI is required for more realistic and accurate results.
- Some studies mentioned the importance of having mutual interactions between buildings and their urban environment [18]. In other words, a two-way coupling between building

energy modeling and urban atmospheric modeling is required especially for mesoscale or microscale analyses.

- It has been reported that dynamic linking between urban atmospheric model and anthropogenic emission model is required [29].
- The importance of integrating buildings and their operation with the urban form to have more realistic results has been clearly demonstrated [82].
- Some modeling simplifications are required to reduce computational costs and to allow more factors to be considered.
- Economic analysis for energy efficiency and renewable energy measures as well as for environmental costs are generally not included in the reported models [102].
- More investigation is required to assess the impacts of having more access to solar radiation for PV generation on reduction of both building energy consumptions and urban air temperatures.

Based on the review of the literature, there is still need for the development of integrated yet flexible simulation environment to effectively model thermal interactions between building energy systems and their urban surroundings. The simulation environment can provide better tool to design and operate urban buildings to optimize their energy efficiency while mitigating the UHI effects. Moreover, future work includes the development of design and retrofit guidelines for urban buildings to enhance the sustainability of urban centers.

Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request. The authors attest that all data for this study are included in the paper. No data, models, or code were generated or used for this paper.

References

[1] Baklanov, A., Lawrence, M., Pandis, S., Mahura, A., Finardi, S., Moussiopoulos, N., Beekmann, M., et al., 2010, "MEGAPOLI: Concept of Multi-Scale Modelling of Megacity Impact on Air Quality and Climate," Adv. Sci. Res., **4**(1), pp. 115–120.

[2] UN-HABITAT, 2013, "State of the World's Cites 2012/2013: United Nations Human Settlements Programme," United Nations Hum. Settlements Program, Nairobi, Kenya, p. 152.

[3] United Nations, 2014, World Urbanization Prospects: The 2014 Revision, Highlights (ST/ESA/SER.A/352), Department of Economic and Social Affairs, Population Division, United Nations, New York.

[4] Madlener, R., and Sunak, Y., 2011, "Impacts of Urbanization on Urban Structures and Energy Demand: What Can We Learn for Urban Energy Planning and Urbanization Management?," Sustain. Cities Soc., **1**(1), pp. 45–53.

[5] Duarte, D. H. S., Shinzato, P., Gusson, C. d. S., and Alves, C. A., 2015, "The Impact of Vegetation on Urban Microclimate to Counterbalance Built Density in a Subtropical Changing Climate," Urban Clim., **14**(Part 2), pp. 224–239.

[6] Imhoff, M. L., Zhang, P., Wolfe, R. E., and Bounoua, L., 2010, "Remote Sensing of the Urban Heat Island Effect Across Biomes in the Continental USA," Remote Sens. Environ., **114**(3), pp. 504–513.

[7] Landsberg, H. E., 1981, *The Urban Climate*, Academic Press, Inc, New York.

[8] Arnfield, A. J., 2003, "Two Decades of Urban Climate Research: A Review of Turbulence, Exchanges of Energy and Water, and the Urban Heat Island," Int. J. Climatol., **23**(1), pp. 1–26.

[9] Stewart, I. D., 2011, "A Systematic Review and Scientific Critique of Methodology in Modern Urban Heat Island Literature," Int. J. Climatol., **31**(2), pp. 200–217.

[10] Aguilar, E., Auer, I., Brunet, M., Peterson, T. C., and Wieringa, J., 2003, "Guidance on Metadata and Homogenization," Wmo Td, **1186**(Oct.), p. 53.

[11] Oke, T. R., 2004, "Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites," World Meteorol. Organ., 81, p. 51, WMO/TD No. 1250, Geneva, Switzerland.

[12] Mirzaei, P. A., and Haghighat, F., 2010, "Approaches to Study Urban Heat Island—Abilities and Limitations," Build. Environ., **45**(10), pp. 2192–2201.

[13] Kalkstein, L. S., and Davis, R. E., 1989, "Weather and Human Mortality: An Evaluation of Demographic and Interregional Responses in the United States," Ann. Assoc. Am. Geogr., **79**(1), pp. 44–64.

[14] Thorsson, S., Lindberg, F., Björklund, J., Holmer, B., and Rayner, D., 2011, "Potential Changes in Outdoor Thermal Comfort Conditions in Gothenburg, Sweden Due to Climate Change: The Influence of Urban Geometry," Int. J. Climatol., **31**(2), pp. 324–335.

[15] Ohashi, Y., Ihara, T., Kikegawa, Y., and Sugiyama, N., 2016, "Numerical Simulations of Influence of Heat Island Countermeasures on Outdoor Human Heat Stress in the 23 Wards of Tokyo, Japan," Energy Build., **114**, pp. 104–111.

[16] Bueno, B., Norford, L., Pigeon, G., and Britter, R., 2011, "Combining a Detailed Building Energy Model With a Physically-Based Urban Canopy Model," Bound.-Layer Meteorol., **140**(3), pp. 471–489.

[17] Kolokotroni, M., Davies, M., Croxford, B., Bhuiyan, S., and Mavrogianni, A., 2010, "A Validated Methodology for the Prediction of Heating and Cooling Energy Demand for Buildings Within the Urban Heat Island: Case-Study of London," Sol. Energy, **84**(12), pp. 2246–2255.

[18] Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., and Wang, M., 2014, "Anthropogenic Heating of the Urban Environment Due to Air Conditioning," J. Geophys. Res. Atmos., **119**(10), pp. 5949–5965.

[19] Kuttler, W., 2008, "The Urban Climate–Basic and Applied Aspects," *Urban Ecology*, Springer, Boston, MA, pp. 233–248.

[20] Kondo, A., Ueno, M., Kaga, A., and Yamaguchi, K., 2001, "The Influence of Urban Canopy Configuration on Urban Albedo," Bound.-Layer Meteorol, **100**(2), pp. 225–242.

[21] de Munck, C., Pigeon, G., Masson, V., Meunier, F., Bousquet, P., Tréméac, B., Merchat, M., Poeuf, P., and Marchadier, C., 2013, "How Much Can Air Conditioning Increase Air Temperatures for a City Like Paris, France?," Int. J. Climatol., **33**(1), pp. 210–227.

[22] Bueno, B., Norford, L., Hidalgo, J., and Pigeon, G., 2013, "The Urban Weather Generator," J. Build. Perform. Simul., **6**(Nov.), pp. 269–281.

[23] Coseo, P., and Larsen, L., 2014, "How Factors of Land use/Land Cover, Building Configuration, and Adjacent Heat Sources and Sinks Explain Urban Heat Islands in Chicago," Landsc. Urban Plan., **125**, pp. 117–129.

[24] Brian Stone, J., 2012, *The City and the Coming Climate: Climate Change in the Places We Live*, Cambridge University Press, Cambridge, UK.

[25] Bernabé, A., Musy, M., Andrieu, H., and Calmet, I., 2015, "Radiative Properties of the Urban Fabric Derived From Surface Form Analysis: A Simplified Solar Balance Model," Sol. Energy, **122**, pp. 156–168.

[26] Lobaccaro, G., Fiorito, F., Masera, G., and Poli, T., 2012, "District Geometry Simulation: A Study for the Optimization of Solar Facades in Urban Canopy Layers," Energy Procedia, **30**, pp. 1163–1172.

[27] Chow, W. T. L., Salamanca, F., Georgescu, M., Mahalov, A., Milne, J. M., and Ruddell, B. L., 2014, "A Multi-Method and Multi-Scale Approach for Estimating City-Wide Anthropogenic Heat Fluxes," Atmos. Environ., **99**, pp. 64–76.

[28] Zhang, G. J., Cai, M., and Hu, A., 2013, "Energy Consumption and the Unexplained Winter Warming Over Northern Asia and North America," Nat. Clim. Change, **3**(5), pp. 466–470.

[29] Sailor, D. J., 2011, "A Review of Methods for Estimating Anthropogenic Heat and Moisture Emissions in the Urban Environment," Int. J. Climatol., **31**(2), pp. 189–199.

[30] Quah, A. K. L., and Roth, M., 2012, "Diurnal and Weekly Variation of Anthropogenic Heat Emissions in a Tropical City, Singapore," Atmos. Environ., **46**, pp. 92–103.

[31] Pigeon, G., Zibouche, K., Bueno, B., Le Bras, J., and Masson, V., 2014, "Improving the Capabilities of the Town Energy Balance Model With Up-to-Date Building Energy Simulation Algorithms: An Application to a Set of Representative Buildings in Paris," Energy Build., **76**, pp. 1–14.

[32] Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., Wang, M., and Svoma, B. M., 2013, "Assessing Summertime Urban Air Conditioning Consumption in a Semiarid Environment," Environ. Res. Lett., **8**(3), p. 034022.

[33] Martilli, A., Clappier, A., and Rotach, M. W., 2002, "An Urban Surface Exchange Parameterisation for Mesoscale Models," Bound.-Layer Meteorol., **104**(2), pp. 261–304.

[34] Martilli, A., 2009, "On the Derivation of Input Parameters for Urban Canopy Models From Urban Morphological Datasets," Bound.-Layer Meteorol., **130**(2), pp. 301–306.

[35] Allegrini, J., Dorer, V., and Carmeliet, J., 2015, "Coupled CFD, Radiation and Building Energy Model for Studying Heat Fluxes in an Urban Environment With Generic Building Configurations," Sustain. Cities Soc., **19**, pp. 385–394.

[36] Bueno, B., Norford, L., Pigeon, G., and Britter, R., 2012, "A Resistance-Capacitance Network Model for the Analysis of the Interactions Between the Energy Performance of Buildings and the Urban Climate," Build. Environ., **54**, pp. 116–125.

[37] Thapar, H., and Yannas, S., 2008, "Microclimate and Urban Form in Dubai," PLEA 2008–25th Conference on Passive and Low Energy Architecture, Dublin, Ireland, Oct. 22–24, pp. 20–25.

[38] "ENVI-met." 2004, https://www.envi-met.com/, Accessed September 20, 2019.

[39] Hedquist, B. C., and Brazel, A. J., 2014, "Seasonal Variability of Temperatures and Outdoor Human Comfort in Phoenix, Arizona, U.S.A," Build. Environ., **72**, pp. 377–388.

[40] Rajagopalan, P., Lim, K. C., and Jamei, E., 2014, "Urban Heat Island and Wind Flow Characteristics of a Tropical City," Sol. Energy, **107**, pp. 159–170.

[41] Gros, A., Bozonnet, E., Inard, C., and Musy, M., 2016, "Simulation Tools to Assess Microclimate and Building Energy—A Case Study on the Design of a new District," Energy Build., **114**, pp. 112–122.

[42] Ng, E., Chen, L., Wang, Y., and Yuan, C., 2012, "A Study on the Cooling Effects of Greening in a High-Density City: An Experience From Hong Kong," Build. Environ., **47**(1), pp. 256–271.
[43] Hall, T. C., Britter, R. E., and Norford, L. K., 2012, "Predicting Velocities and Turbulent Momentum Exchange in Isolated Street Canyons," Atmos. Environ., **59**, pp. 75–85.
[44] Li, X. X., Liu, C. H., Leung, D. Y. C., and Lam, K. M., 2006, "Recent Progress in CFD Modelling of Wind Field and Pollutant Transport in Street Canyons," Atmos. Environ., **40**(29), pp. 5640–5658.
[45] Baik, J. J., and Kim, J. J., 1999, "A Numerical Study of Flow and Pollutant Dispersion Characteristics in Urban Street Canyons," J. Appl. Meteorol., **38**(11), pp. 1576–1589.
[46] Soulhac, L., Garbero, V., Salizzoni, P., Mejean, P., and Perkins, R. J., 2009, "Flow and Dispersion in Street Intersections," Atmos. Environ., **43**(18), pp. 2981–2996.
[47] Oke, T. R., 1988, "Street Design and Urban Canopy Layer Climate," Energy Build., **11**(1–3), pp. 103–113.
[48] Sini, J. F., Anquetin, S., and Mestayer, P. G., 1996, "Pollutant Dispersion and Thermal Effects in Urban Street Canyons," Atmos. Environ., **30**(15), pp. 2659–2677.
[49] Kim, J. J., and Baik, J. J., 2001, "Urban Street-Canyon Flows With Bottom Heating," Atmos. Environ., **35**(20), pp. 3395–3404.
[50] He, L., Hang, J., Wang, X., Lin, B., Li, X., and Lan, G., 2017, "Numerical Investigations of Flow and Passive Pollutant Exposure in High-Rise Deep Street Canyons With Various Street Aspect Ratios and Viaduct Settings," Sci. Total Environ., **584**, pp. 189–206.
[51] Raasch, S., and Schröter, M., 2001, "PALM—A Large-Eddy Simulation Model Performing on Massively Parallel Computers," Meteorol. Zeitschrift, **10**(5), pp. 363–372.
[52] Keck, M., Raasch, S., Letzel, M. O., and Ng, E., 2014, "First Results of High Resolution Large-Eddy Simulations of the Atmospheric Boundary Layer," J. Heat Isl. Inst. Int., **9**(2), pp. 39–43.
[53] Vardoulakis, S., Fisher, B. E. A., Pericleous, K., and Gonzalez-Flesca, N., 2003, "Modelling Air Quality in Street Canyons: A Review," Atmos. Environ., **37**(2), pp. 155–182.
[54] Li, X. X., Britter, R. E., Koh, T. Y., Norford, L. K., Liu, C. H., Entekhabi, D., and Leung, D. Y., 2010, "Large-Eddy Simulation of Flow and Pollutant Transport in Urban Street Canyons With Ground Heating," Bound.-Layer Meteorol., **137**(2), pp. 187–204.
[55] Nazarian, N., and Kleissl, J., 2016, "Realistic Solar Heating in Urban Areas: Air Exchange and Street-Canyon Ventilation," Build. Environ., **95**, pp. 75–93.
[56] Thaker, P., and Gokhale, S., 2016, "The Impact of Traffic-Flow Patterns on Air Quality in Urban Street Canyons," Environ. Pollut., **208**, pp. 161–169.
[57] Dobre, A., Arnold, S. J., Smalley, R. J., Boddy, J. W. D., Barlow, J. F., Tomlin, A. S., and Belcher, S. E., 2005, "Flow Field Measurements in the Proximity of an Urban Intersection in London, UK," Atmos. Environ., **39**(26), pp. 4647–4657.
[58] Soulhac, L., Perkins, R. J., and Salizzoni, P., 2008, "Flow in a Street Canyon for Any External Wind Direction," Bound.-Layer Meteorol., **126**(3), pp. 365–388.
[59] Huang, H., Akutsu, Y., Arai, M., and Tamura, M., 2000, "A Two-Dimensional Air Quality Model in an Urban Street Canyon: Evaluation and Sensitivity Analysis," Atmos. Environ., **34**(5), pp. 689–698.
[60] Wang, W., Raasch, S., Yim, S., Ho, J., and Ng, E., 2015, "Parametric Studies of Urban Morphologies of High Density Cities and Their Air Ventilation Performance Under Neutral and Unstable Atmospheric Conditions Using Advanced Large-Eddy Simulations," The 9th International Conference on Urban Climate (ICUC), Toulouse, France, July 20–24, pp. 1–18.
[61] Gutiérrez, E., Martilli, A., Santiago, J. L., and González, J. E., 2015, "A Mechanical Drag Coefficient Formulation and Urban Canopy Parameter Assimilation Technique for Complex Urban Environments," Bound.-Layer Meteorol., **157**(2), pp. 333–341.
[62] Taha, H., 2013, "The Potential for Air-Temperature Impact From Large-Scale Deployment of Solar Photovoltaic Arrays in Urban Areas," Sol. Energy, **91**, pp. 358–367.
[63] Cortes, A., Murashita, Y., Matsuo, T., Kondo, A., Shimadera, H., and Inoue, Y., 2015, "Numerical Evaluation of the Effect of Photovoltaic Cell Installation on Urban Thermal Environment," Sustain. Cities Soc., **19**, pp. 250–258.
[64] Masson, V., Bonhomme, M., Salagnac, J.-L., Briottet, X., and Lemonsu, A., 2014, "Solar Panels Reduce Both Global Warming and Urban Heat Island," Front. Environ. Sci., **2**(June), pp. 1–10.
[65] Tian, W., Wang, Y., Xie, Y., Wu, D., Zhu, L., and Ren, J., 2007, "Effect of Building Integrated Photovoltaics on Microclimate of Urban Canopy Layer," Build. Environ., **42**(5), pp. 1891–1901.
[66] Lobaccaro, G., Fiorito, F., Masera, G., and Prasad, D., 2012, "Urban Solar District: A Case Study of Geometric Optimization of Solar Façades for a Residential Building in Milan," 50th Annual Conference, Australian Solar Energy Society, Melbourne, Australia, Dec. 6–7, Australian Solar Energy Society, pp. 1–10.
[67] Hamdi, R., Kusaka, H., Doan, Q. V., Cai, P., He, H., Luo, G., Kuang, W., et al., 2020, "The State-of-the-Art of Urban Climate Change Modeling and Observations," Earth Syst. Environ., **4**(4), pp. 631–646.
[68] Mirzaei, P. A., 2015, "Recent Challenges in Modelling of Urban Heat Island," Sustain. Cities Soc., **19**, pp. 200–206.
[69] Ichinose, T., Shimodozono, K., and Hanaki, K., 1999, "Impact of Anthropogenic Heat on Urban Climate in Tokyo," Atmos. Environ., **33**(24–25), pp. 3897–3909.
[70] Pielke, R. A., 1973, *A Three-Dimensional Numerical Model of the Sea Breezes Over South Florida*, American Meteorological Society, Boston, MA.
[71] Masson, V., 2000, "A Physically-Based Scheme for the Urban Energy Budget in Atmospheric Models," Bound.-Layer Meteorol., **94**(3), pp. 357–397.
[72] Kusaka, H., Kondo, H., Kikegawa, Y., and Kimura, F., 2001, "A Simple Single-Layer Urban Canopy Model for Atmospheric Models: Comparison With Multi-Layer and Slab Models," Bound.-Layer Meteorol., **101**(3), pp. 329–358.
[73] Salamanca, F., Krpo, A., Martilli, A., and Clappier, A., 2010, "A New Building Energy Model Coupled With an Urban Canopy Parameterization for Urban Climate Simulations-Part I. Formulation, Verification, and Sensitivity Analysis of the Model," Theor. Appl. Climatol., **99**(3–4), pp. 331–344.
[74] Salamanca, F., and Martilli, A., 2010, "A New Building Energy Model Coupled With an Urban Canopy Parameterization for Urban Climate Simulations-Part II. Validation With One Dimension off-Line Simulations," Theor. Appl. Climatol., **99**(3–4), pp. 345–356.
[75] Chen, F., Kusaka, H., Bornstein, R., Ching, J., Grimmond, C. S. B., Grossman-Clarke, S., Loridan, T., et al., 2011, "The Integrated WRF/Urban Modelling System: Development, Evaluation, and Applications to Urban Environmental Problems," Int. J. Climatol., **31**(2), pp. 273–288.
[76] Kusaka, H., Chen, F., Tewari, M., Dudhia, J., Gill, D. O., Duda, M. G., Wang, W., and Miya, Y., 2012, "Numerical Simulation of Urban Heat Island Effect by the WRF Model With 4-km Grid Increment: An Inter-Comparison Study Between the Urban Canopy Model and Slab Model," J. Meteorol. Soc. Japan, **90**, pp. 33–45.
[77] Kusaka, H., Hara, M., and Takane, Y., 2012, "Urban Climate Projection by the WRF Model at 3-km Horizontal Grid Increment: Dynamical Downscaling and Predicting Heat Stress in the 2070's August for Tokyo, Osaka, and Nagoya Metropolises," J. Meteorol. Soc. Japan, **90**, pp. 47–63.
[78] Masson, V., 2006, "Urban Surface Modeling and the Meso-Scale Impact of Cities," Theor. Appl. Climatol., **84**(1–3), pp. 35–45.
[79] Chen, D., Wang, X., Thatcher, M., Barnett, G., Kachenko, A., and Prince, R., 2014, "Urban Vegetation for Reducing Heat Related Mortality," Environ. Pollut., **192**, pp. 275–284.
[80] Klok, L., Zwart, S., Verhagen, H., and Mauri, E., 2012, "The Surface Heat Island of Rotterdam and Its Relationship With Urban Surface Characteristics," Resour. Conserv. Recycl., **64**, pp. 23–29.
[81] Asawa, T., Hoyano, A., and Nakaohkubo, K., 2008, "Thermal Design Tool for Outdoor Spaces Based on Heat Balance Simulation Using a 3D-CAD System," Build. Environ., **43**(12), pp. 2112–2123.
[82] Quan, S. J., Wu, J., Wang, Y., Shi, Z., Yang, T., and Yang, P. P.-J., 2016, "Urban Form and Building Energy Performance in Shanghai Neighborhoods," Energy Procedia, **88**, pp. 126–132.
[83] Targhi, M. Z., and Van Dessel, S., 2015, "Potential Contribution of Urban Developments to Outdoor Thermal Comfort Conditions: The Influence of Urban Geometry and Form in Worcester, Massachusetts, USA," Procedia Eng., **118**, pp. 1153–1161.
[84] Huber, J., and Nytsch-Geusen, C., 2011, "Development of Modeling and Simulation Strategies for Large Scale Urban Districts," Build. Simulation, Sydney Aust., **1753–1760**, pp. 14–16.
[85] Cerezo Davila, C., Reinhart, C. F., and Bemis, J. L., 2016, "Modeling Boston: A Workflow for the Efficient Generation and Maintenance of Urban Building Energy Models From Existing Geospatial Datasets," Energy, **117**, pp. 237–250.
[86] Reinhart, C. F., and Cerezo Davila, C., 2016, "Urban Building Energy Modeling—A Review of a Nascent Field," Build. Environ., **97**, pp. 196–202.
[87] Kavgic, M., Mavrogianni, A., Mumovic, D., Summerfield, A., Stevanovic, Z., and Djurovic-Petrovic, M., 2010, "A Review of Bottom-Up Building Stock Models for Energy Consumption in the Residential Sector," Build. Environ., **45**(7), pp. 1683–1697.
[88] Reinhart, C. F., Dogan, T., Jakubiec, J. A., Rakha, T., and Sang, A., 2013, "Umi—An Urban Simulation Environment for Building Energy Use, Daylighting and Walkability," 13th Conference of International Building Performance Simulation Association, Chambery, France, Aug. 25–28, pp. 476–483.
[89] Ahmad, A., 2004, "Energy Simulation for a Typical House Built With Different Types of Masonry Building Materials," Arab. J. Sci. Eng., **29**(2), pp. 113–126.
[90] Al-Ragom, F., 2003, "Retrofitting Residential Buildings in Hot and Arid Climates," Energy Convers. Manage., **44**(14), pp. 2309–2319.
[91] Alaidroos, A., and Krarti, M., 2015, "Optimal Design of Residential Building Envelope Systems in the Kingdom of Saudi Arabia," Energy Build., **86**, pp. 104–117.
[92] Al-Homoud, M. S., 2004, "The Effectiveness of Thermal Insulation in Different Types of Buildings in Hot Climates," J. Therm. Envel. Build. Sci., **27**(3), pp. 235–247.
[93] Al-saadi, S. N., and Budaiwi, I. M., 2007, "Performance-Based Envelope Design for Residential Buildings in Hot Climates," Proceedings of Building Simulation, Beijing, China, Sept. 3–6, pp. 1726–1733.
[94] Ameer, B., and Krarti, M., 2016, "Impact of Subsidization on High Energy Performance Designs for Kuwaiti Residential Buildings," Energy Build., **116**, pp. 249–262.
[95] Kikegawa, Y., Genchi, Y., Yoshikado, H., and Kondo, H., 2003, "Development of a Numerical Simulation System Toward Comprehensive Assessments of Urban Warming Countermeasures Including Their Impacts Upon the Urban Buildings' Energy-Demands," Appl. Energy, **76**(4), pp. 449–466.
[96] Tanimoto, J., Hagishima, A., and Chimklai, P., 2004, "An Approach for Coupled Simulation of Building Thermal Effects and Urban Climatology," Energy Build., **36**(8), pp. 781–793.
[97] Bueno, B., Pigeon, G., Norford, L. K., Zibouche, K., and Marchadier, C., 2012, "Development and Evaluation of a Building Energy Model Integrated in the TEB Scheme," Geosci. Model Dev., **5**(2), pp. 433–448.

[98] Gros, A., Bozonnet, E., and Inard, C., 2014, "Cool Materials Impact at District Scale—Coupling Building Energy and Microclimate Models," Sustain. Cities Soc., **13**, pp. 254–266.
[99] Fonseca, J. A., and Schlueter, A., 2015, "Integrated Model for Characterization of Spatiotemporal Building Energy Consumption Patterns in Neighborhoods and City Districts," Appl. Energy, **142**, pp. 247–265.
[100] Rodriguez-Alvarez, J., 2016, "Urban Energy Index for Buildings (UEIB): A New Method to Evaluate the Effect of Urban Form on Buildings' Energy Demand," Landsc. Urban Plan., **148**, pp. 170–187.
[101] Gracik, S., Heidarinejad, M., Liu, J., and Srebric, J., 2015, "Effect of Urban Neighborhoods on the Performance of Building Cooling Systems," Build. Environ., **90**, pp. 15–29.
[102] Robinson, D., Campbell, N., Gaiser, W., Kabel, K., Le-Mouel, A., Morel, N., Page, J., Stankovic, S., and Stone, A., 2007, "SUNtool—A New Modelling Paradigm for Simulating and Optimising Urban Sustainability," Sol. Energy, **81**(9), pp. 1196–1211.
[103] Ohashi, Y., Kikegawa, Y., Ihara, T., and Sugiyama, N., 2014, "Numerical Simulations of Outdoor Heat Stress Index and Heat Disorder Risk in the 23 Wards of Tokyo," J. Appl. Meteorol. Climatol., **53**(3), pp. 583–597.
[104] Taleghani, M., Kleerekoper, L., Tenpierik, M., and van den Dobbelsteen, A., 2014, "Outdoor Thermal Comfort Within Five Different Urban Forms in the Netherlands," Build. Environ., **83**, pp. 65–78.
[105] Suri, M., and Hofierka, J., 2004, "A New GIS-Based Solar Radiation Model and Its Application to Photovoltaic Assessments," Trans. GIS, **8**(2), pp. 175–190.
[106] Robinson, D., and Stone, A., 2004, "Solar Radiation Modelling in the Urban Context," Sol. Energy, **77**(3), pp. 295–309.
[107] Chow, W. T. L., and Brazel, A. J., 2012, "Assessing Xeriscaping as a Sustainable Heat Island Mitigation Approach for a Desert City," Build. Environ., **47**(1), pp. 170–181.
[108] Declet-Barreto, J., Brazel, A. J., Martin, C. A., Chow, W. T. L., and Harlan, S. L., 2013, "Creating the Park Cool Island in an Inner-City Neighborhood: Heat Mitigation Strategy for Phoenix, AZ," Urban Ecosyst., **16**(3), pp. 617–635.
[109] Scherba, A., Sailor, D. J., Rosenstiel, T. N., and Wamser, C. C., 2011, "Modeling Impacts of Roof Reflectivity, Integrated Photovoltaic Panels and Green Roof Systems on Sensible Heat Flux Into the Urban Environment," Build. Environ., **46**(12), pp. 2542–2551.