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Review

Urban heat island impacts on building energy consumption: A review of approaches and findings

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A B S T R A C T

Urban heat island (UHI) could have significant impacts on building energy consumption by increasing space cooling demand and decreasing space heating demand. However, the impacts of UHI on building energy consumption were understudied due to challenges associated with quantifying UHI-induced temperature change and evaluating building energy consumption. In this study, we reviewed existing literature for improving the understanding of UHI impacts on building energy consumption. It was found that UHI could result in a median increase of 19.0% in cooling energy consumption and a median decrease of 18.7% in heating energy consumption. The reported UHI impacts showed strong intercity variations with an increase of cooling energy consumption from 10% to 120% and a decrease of heating energy consumption from 3% to 45%. The UHI impacts also showed clear intra-city variations with stronger impacts in urban center than that in urban periphery. There were significant differences in the method and the data used to evaluate the UHI impacts in previous studies. Four future research focuses were recommended to better understand the UHI impacts on building energy consumption.

Contents

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1. Introduction

The building sector is an important component of the energy system and accounts for approximately 31% (22–57% at the regional level) of global final energy consumption [1]. Global building energy consumption has been increasing steadily due to rapid urbanization, climate change, and other driving factors [2–4]. It increased from 1.4 billion tonnes oil equivalent (TOE) in 1970 to 3.6 billion TOE in 2010 and was projected to increase to 5.5 billion TOE in 2040 [5]. The large amount of building energy consumption has raised great challenges for sustainable development such as interrupting reliable energy supply, increasing greenhouse gas emissions, and exacerbating air pollution [4,6,7]. It is not surprising that a better understanding of building energy consumption, including its spatiotemporal pattern, driving factors, and environmental impacts, has become a hot topic attracting attentions of both scientific communities and decision makers.

Building energy consumption is influenced by multiple factors such as ambient temperature, building characteristics, the performance and schedule of appliances (e.g., lighting, heating, ventilating, and air conditioning systems), occupant activities [1,4,8–12], etc. Among them, ambient temperature is one of the most important factors as it directly drives the operation of cooling/heating system and influences the corresponding building cooling and heating energy consumption, which accounts for about half of the total building energy consumption in the United States (U.S.) [2]. Ambient temperature is affected by both global and local climate change. Rising temperature and extreme events caused by climate change have been identified as one of the most significant drivers of building energy consumption [13–18]. The review of case studies showed that the building peak electricity load would increase up to 4.6% for one degree of temperature increase and the corresponding increase of total electricity consumption was estimated as high as 8.5% [19]. Using the long-term modeling results of the integrated Global Change Assessment Model (GCAM), Zhou et al. [18] found that climate change may decrease the building sector's final energy consumption by up to 6% in both the U.S. and China by the end of this century, but increase cooling energy consumption by 20–35% and 37–41%, respectively in the U.S. and China.

In addition to the warming induced by long-term climate change, urban areas where more than half of global population reside also experience local warming with temperature in the urban areas higher than that in the surrounding rural areas, known as urban heat island (UHI) effect. UHI is now a worldwide phenomenon observed in cities regardless of their locations and sizes [20–26]. It is widely acknowledged that the UHI can increase building cooling energy consumption and decrease building heating energy consumption [17,27–30]. Santamouris [31] summarized the published case studies and found that the cooling load of typical buildings in urban areas is on average 13% higher than that in rural areas. UHI has small spatial extent as it is usually confined within urban areas, which only cover 1–3% of global land [32–34]. However the UHI impacts on building energy consumption are nontrivial because a majority of buildings and building energy consumption are in urban areas. As urbanization usually increases UHI intensity [24,35], it is projected that cities in future will experience even a higher temperature increase compared to the surrounding rural areas and this would result in a significant change in building energy consumption and total energy demand [36]. Therefore, a thorough and quantitative understanding of the UHI impacts on building energy consumption is of great importance for designing sustainable energy infrastructure.

Though it has been widely acknowledged that UHI has significant impacts on building energy consumption and these impacts should be explicitly considered in building energy consumption modeling, only a limited number of studies quantified this impacts because of the challenges in preparing temperature data with and without UHI effect and in simulating the corresponding building energy consumption. Currently, our knowledge of the UHI impacts on building energy consumption, including their magnitudes, spatiotemporal patterns, driving factors, and ecological and environmental consequences, are still limited.

In this paper, we performed a comprehensive review of current case studies for a better understanding of the UHI impacts on building energy consumption. First, we identified the commonly used approaches for quantifying the UHI impacts on building energy consumption and their respective advantages and disadvantages. Second, we examined the reported quantitative UHI impacts in the literature and their spatial variations within and among cities. Findings of this review will help better understand different modeling approaches and the selection of suitable approaches in practice. The reviewed quantitative UHI impacts and their spatial variations within and among cities will help energy infrastructure planning and investment, especially under the condition of global climate change and rapid urbanization. The remainder of this paper was arranged as follows. Section 2 described the procedure of literature search and the extraction of key information. Section 3 reviewed current approaches for studying the UHI impacts on building energy consumption and their advantages and limitations. Section 4 summarized previously reported UHI impacts and their spatial variations within and among cities. Section 5 discussed the challenges of modeling the UHI impacts on building energy consumption and proposed future research focuses. The conclusions were drawn in Section 6.

2. Status of modeling UHI impacts on building energy consumption in the literature

The UHI impacts on building energy consumption were usually modeled as the difference in the building energy consumptions with and without UHI effect. It involves three key components. The first is preparing/generating air temperature datasets with and without UHI effect, the second is estimating building energy consumptions based on these datasets, and the third is comparing the results of these two estimations. A variety of different approaches have been used for this purpose in existing studies. These studies vary in 1) the methods and data for measuring UHI, 2) the models and related parameters for estimating building energy consumption, and 3) the reported values of the UHI impacts. We reviewed relevant literature of these different methods and discussed their advantages and limitations. We summarized the UHI impacts on building energy consumption at regional and global level by calculating the median of the UHI impacts (i.e., percent change) reported in the case studies. The spatial variations of the UHI impacts within and among cities were also investigated.

We searched relevant papers published in peer-reviewed journals in English from databases of Web of Science, Wiley Online Library, Scopus, and Google Scholar. We used the search terms of "urban heat island" or "UHI" combined with "building energy use" or "building energy consumption" to include relevant articles. During the literature search, we used the "snowballing" method by checking the bibliographies of relevant articles to ensure a comprehensive review of the literature [37]. We only included studies that explicitly reported the quantitative UHI impacts on building energy consumption. Moreover, to have a coherent review of the UHI impacts on building energy consumption, we excluded studies that only reported the UHI impacts on cooling/heating degree day, e.g., by Schatz and Kucharik [38] and Vardoulakis et al. [39] and that focused on the role of UHI countermeasures in reducing building cooling energy consumption, e.g., by Santamouris et al. [40] and Roman et al. [41]. Finally, 24 peer-reviewed papers were included for further quantitative analyses as listed in Table 1.

We extracted the following information from the reviewed case studies: (1) study area (city), (2) UHI impact, specifically the relative change of building energy consumption by UHI, (3) reported maximum UHI intensity, (4) temperature data and method used to calculate UHI (5) study scale (i.e., the city level), or building type and size if at the building level, (6) Building energy consumption modeling/estimation method, and (7) set-point if using physics-based model. To compare the UHI impacts among cities, we treated studies of the same city (e.g., London, UK, and Athens, Greece) in different papers and different cities in the same paper (e.g. Refs. [29,42]) as unique samples.

Table 1
Summary of UHI impacts on building energy consumption reported in the surveyed 24 papers.

Location, publication year	Impacts	UHI (°C)	Temperature data[a]	UHI estimation[b]	Analyzing building	Energy estimation method[c]	Set point (°C)	Reference
Cooling								
Western Athens, Greece, 2000	➢ 66% (in 1997) and 33% (in 1998, hotter year) increase in cooling energy ➢ 99% (in 1997) and 30% (in 1998) increase in peak cooling power	6	U vs R (July in 1997 and 1998)	4U_1R	Simulated for a four-apartment building (320m^2) and upgraded to the city level residential buildings (177385 dwellings)	PBM: DOE2.1.E	26	[51]
Athens, Greece, 2001	➢ 120% increase in cooling load ➢ 100% increase in peak electricity demand	10	U vs R (summer, 1997)	33U_1R	A typical office (500 m^2)	PBM: TRNSYS	26	[46]
London, UK, 2006	➢ 19% increase in cooling energy ➢ The impacts are close for a typical hot week and an extremely hot week	7	U vs R (one hot week in 1999 and 2000)	1U_1R	A typical office (60 m^2)	PBM: BRE's 3 TC	24	[96]
London, UK, 2002, 2007	➢ Up to 25% increase in cooling load	6	U vs R (August 1999–July 2000)	23U_1R	A typical office (450 m^2)	PBM: TAS	24	[47,48]
Hong Kong, China, 2011	➢ 10% increase in air-conditioning demand	1.8	Observed UHI (May–October 2010)+TMY vs TMY	4Uavg_1R	An office (1296 m^2) and a residential flat (95 m^2)	PBM: EnergyPlus	25.5	[59]
Tokyo, Japan, 2012	➢ 27.5% increase in cooling energy	2.5	Simulated U vs simulated R	Gridded	All buildings of nine types at the city level	STM (based on multiple years data)	–	[63]
London, UK, 2012	➢33% increase in cooling load in 2000 ➢ 28% increase in cooling load in 2050	NA	U vs R (September 1999–August 2000)	19U_1R	A typical office (1350 m^2)	PBM: IESVE	24	[49]
Bahrain, 2013	➢ Up to 10% increase in cooling electricity consumption	5	U vs R (2009)	5U_1R	82 sampled residential house	STM (based on multiple years data)	–	[50]
Boston, US, 2013	➢ 4–22% or 5–41% increase in cooling energy consumption based on the selection of rural station	1.3 or 2.8	U vs R (2011)	1U_2R	A typical single-family and a small office (size not reported)	PBM: EnergyPlus	NA	[43]
Beijing, China, 2014	➢ 11.28% increase for total cooling electricity consumption ➢ 20.4% increase for peak cooling electricity consumption	2.5	U vs R from other study	Single UHI	City level, all buildings	STM (based on data from May to September in 2005)	–	[90]
Melbourne, Australia, 2014	➢ 8.2–11.4% increase in cooling energy consumption	1	Simulated UHI + R vs R (2003)	Single UHI	Residential buildings (185 m^2 and 1350 m^2)	PBM: AccuRate	NA	[97]
15 US cities, 2014	➢ 13–35% increase in cooling energy consumption	2 (Houston)	Simulated UHI + TMY vs TMY	Multiple UHIs	A typical office (size not reported)	PBM: EnergyPlus	NA	[29]
Modena, Italy, 2015	➢ 10% increase in cooling energy consumption	1.4	U vs R (Summer 2012)	1U_1R	An university library (2200 m^2)	PBM: TRNSYS 17	NA	[91]
		5		Single UHI	82 sampled residential house		–	[89]

(continued on next page)

Table 1 (*continued*)

Location, publication year	Impacts	UHI (°C)	Temperature data[a]	UHI estimation[b]	Analyzing building	Energy estimation method[c]	Set point (°C)	Reference
AMWAJ Islands, Bahrain, 2015	➢ 11–18% increase in cooling energy demand		Simulated inhabited vs uninhabited island			STM (based on multiple years data)		
Singapore, 2016	➢ 4.6–12.18% increase in cooling load	2	simulated U vs R (3 year average)	Multiple UHI levels	An office (24000–180000 m^2)	PBM: IES	NA	[61]
Manchester, UK, 2016	➢ 9.4–12.2% increase in cooling energy consumption	3	TMY + simulated UHI vs TMY (July)	Single UHI	Three office buildings (972 m^2, 3204 m^2, and 5418 m^2)	PBM: IES	23	[28]
Central Taiwan, China, 2017	➢ 61% increase in cooling energy in the 1990s ➢ 52% increase in cooling energy in the 2025s ➢ 27% increase in cooling energy in the 2085s	3	Simulated average U vs average R	Two UHI levels	A residential building (87 m^2)	PBM: EnergyPlus	23	[17]
Beijing, China, 2017	➢ 11% increase in cooling load ➢ 7% increase in cooling peak load	8	Average U vs average R (1961–2014)	7Uavg_10Ravg	An office (size not reported)	PBM: DeST	18	[45]
Singapore, 2017	➢ 4.15–11% increase in cooling energy consumption	1–2	simulated U vs TMY	Three UHI levels	Residential building (size not reported)	PBM: EnergyPlus	NA	[62]
Four South American cities, 2017	➢ 15–200% increase in cooling energy consumption		simulated U vs R	Up to 5 UHI levels	Four types of residential building (size not reported)	PBM: TRNSYS	NA	[42]
Barcelona, Spain, 2017	➢ 18–28% increase in cooling load	4.3	U vs R (2014)	2U_1R	A residential building (size not reported)	PBM: EnergyPlus	23	[27]
Rome, Italy, 2017	➢ 12–46% increase in cooling energy consumption	8	U vs R (Summer in 2015 and 2016)	U4_R1	A residential building (270 m^2)	PBM: TRNSYS	26	[52]
Rome, Italy, 2018	➢ 30% increase in cooling energy consumption	1.4	U vs R (October 2014 to October 2016)	1U_2R	A residential building (72 m^2)	PBM: TRNSYS	NA	[44]
Heating								
Athens, Greece, 2001	➢ 27% decrease in heating load	10	U vs R (winter, 1997)	33U_1R	A typical office (500 m^2)	PBM: TRNSYS	NA	[46]
London, UK, 2002, 2007	➢ Up to 22% decrease in heating load	6	U vs R (August 1999–July 2000)	23U_1R	A typical office (450 m^2)	PBM: TAS	20	[47,48]
Tokyo, Japan, 2012	➢ 18.4% decrease in heating energy consumption	2.5	Simulated U vs simulated R	Gridded	All buildings	STM (based on multiple years data)	–	[63]
London, UK, 2012	➢ 39% decrease in heating load in 2000 ➢ 42% decrease in heating load in 2050	NA	U vs R (September 1999–August 2000)	19U_1R	A typical office (1350 m^2)	PBM: IESVE	21	[49]
Boston, US, 2013	➢ 13–15% decrease in heating energy consumption (based on rural station closer to the city center) ➢ 4–14% decrease in heating energy consumption (based on rural station further away from the city center)	1.3 or 2.8	U vs R (2011)	1U_2R	A typical single-family and a small office building (size not reported)	PBM: EnergyPlus	NA	[43]
Melbourne, Australia, 2014	➢ 0.9–3.1% decrease in heating energy consumption	1	Simulated UHI + R vs R (2003)	1UHI	Residential buildings (185 m^2 and 1350 m^2)	PBM: AccuRate	NA	[97]
15 US cities, 2014	➢ 13–45% decrease in heating energy consumption	2 (Houston)	Simulated UHI + TMY vs TMY	Multiple UHIs	A typical office (size not reported)	PBM: EnergyPlus	NA	[29]
Modena, Italy, 2015	➢ 16% decrease in heating energy consumption	1.4	U vs R (Winter 2012)	1U_1R	A university library (2200 m^2)	PBM: TRNSYS	NA	[91]
Beijing, China, 2017	➢ 16% decrease in heating energy consumption ➢ 9% decrease in heating peak load	2.5	Average U vs average R (1961–2014)	7Uavg_10Ravg	An office (size not reported)	PBM: DeST	26	[45]
Rome, Italy, 2018	➢ 11% decrease in heating energy	1.4	U vs R (October 2014 to October 2016)	1U_2R	Residential building	PBM: TRNSYS	26	[44]
Cooling and heating combined								
Athens, Greece, 2001	➢ 66% increase	10	U vs R	33U_1R	A typical office (500 m^2)	PBM: TRNSYS		[46]

Table 1 (*continued*)

Location, publication year	Impacts	UHI (°C)	Temperature data[a]	UHI estimation[b]	Analyzing building	Energy estimation method[c]	Set point (°C)	Reference
London, UK, 2002, 2007	➢ Up to 9.5% increase	6	U vs R	23U_1R	A typical office (450 m^2)	PBM: TAS		[47,48]
London, UK, 2012	➢ 0.1% decrease in 2000 ➢ 11% increase in 2050	NA	U vs R	19U_1R	A typical office (1350 m^2)	PBM: IESVE		[49]
Tokyo, Japan, 2012	➢ 1% increase in the commercial sector ➢ 8% decrease in the residential sector ➢ 3.7% decrease in all sectors	2.5	Simulated U vs simulated R	Gridded	All buildings	STM (based on multiple years data)		[63]
Boston, US, 2013	➢ 12–15% decrease (based on rural station closer to the city center) ➢ 2–13% decrease (based on rural station further away from the city center)	1.3 or 2.8	U vs R	1U_2R	A typical single-family and a small office building (size not reported)	PBM: EnergyPlus		[43]
15 US cities, 2014	➢ Increase or decrease based on climate zone	2 (Houston)	Simulated UHI + TMY vs TMY		A typical office (size not reported)	PBM: EnergyPlus		[29]
Melbourne, Australia, 2014	➢ 2.3% decrease for a detached single-story ➢ 4.2% decrease for a two-story house		Simulated UHI + R vs R	1UHI	Residential buildings (185 m^2 and 1350 m^2)	PBM: AccuRate		[97]
Modena, Italy, 2015	➢ 1% decrease	1.4	U vs R	1U_1R	A university library (2200 m^2)	PBM: TRNSYS		[91]
Beijing, China, 2017	➢ 3% decrease	2.5	U vs R	reference	An office (size not reported)	PBM: DeST		[45]
Rome, Italy, 2018	➢ 1.7% increase or 7.2% decrease based on the selection of rural weather station	1.4	U vs R	1U_2R	A residential building (72 m^2)	PBM: TRNSYS		[44]

[a] U vs R means temperatures observed from urban and rural observation stations.
[b] Values before U and R mean the number of urban or rural stations, respectively. avg means the average temperature.
[c] PBM means the physics-based model, STM means the statistical model.

We collected the reported UHI impacts on building energy consumption (i.e., percentage change) for each sample using the following scheme. We used the mean value of temperature and building energy consumption, if the data were collected from multiple rural weather stations or multiple buildings. For studies with data collected from multiple urban weather stations, we used the maximum value as many studies reported the maximum UHI impact. We used current or historical climate data and real building operating conditions when the studies also reported the UHI impacts under scenarios of climate and building characteristics. We aggregated the city level results to the regional and global levels by calculating the median value as they are not normally distributed.

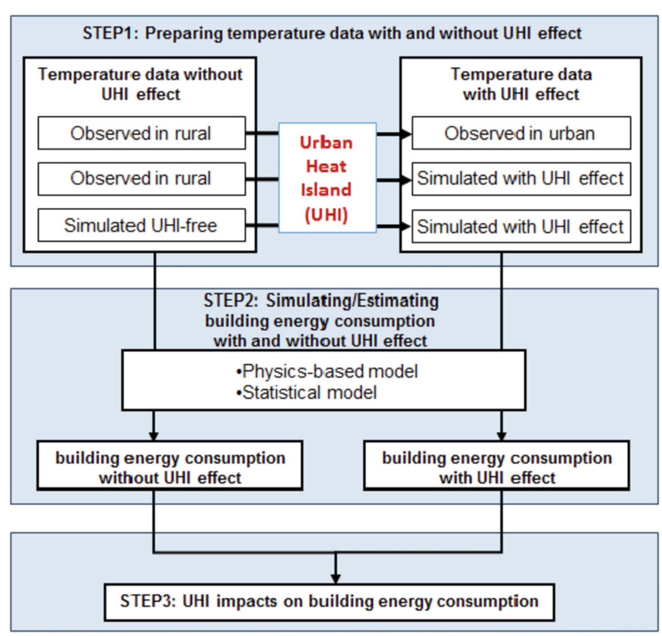

Fig. 1. Flowchart of modeling the UHI impacts on building energy consumption.

3. Procedures in evaluating UHI impacts on building energy consumption

The UHI impacts on building energy consumption were evaluated by comparing two estimations of building energy consumption with and without UHI effect. Practically, the procedure includes three steps: (1) preparing two temperature datasets with and without UHI effect; (2) Simulating/Estimating building energy consumption respectively using two temperature datasets; and (3) evaluating the UHI impacts on building energy consumption by comparing two modeling results (Fig. 1). The remainder of this section will discuss the detail of each step.

3.1. Temperature data with and without UHI effect

Preparing the two temperature datasets with and without UHI effect is the first and fundamental step to evaluate the UHI impacts on building energy consumption. We grouped the used approaches into three general categories based on how the temperature data

Table 2
Advantages and disadvantages of three common approaches for preparing temperature data with and without UHI effect.

Approaches	Advantages	Disadvantages
Observed urban and rural temperatures	➢ Easy data accessibility ➢ High temporal resolution ➢ Long temporal coverage	➢ Large uncertainty due to a limited number of rural stations ➢ Limited spatial coverage of urban stations
Simulated urban and observed rural temperatures	➢ Better capture of the intra-city variations of UHI ➢ Effective evaluation of urban (greenspace) planning strategies	➢ Difficult to simulate urban temperature ➢ Still influenced by the limited number of rural stations
Simulated urban and rural temperatures	➢ A full spatial coverage ➢ Effective evaluation of urban (greenspace) planning strategies	➢ Time-consuming ➢ Require lots of auxiliary datasets.

were produced (Fig. 1). We summarized their corresponding advantages and disadvantages as listed in Table 2.

3.1.1. *Observed urban and rural temperatures*

The most widely used temperature data to study the UHI impacts on building energy consumption are temperatures from in-situ observations in urban and rural areas. Specifically, more than half of the 24 studies used this approach (Table 1 and Fig. 2a). This is not surprising as the UHI intensity was traditionally defined as temperature difference between urban and rural areas, and air temperature from in-situ stations is easily accessible. Most studies used observation data at only one station (e.g., airport) to represent the rural (UHI-free) background temperature (Fig. 3), except for Street et al. [43] and Guattari et al. [44] who used rural temperature data from two airports. Both of them found large differences in the modeled UHI impacts on building energy consumption using temperature data at different rural stations. For example, Street et al. [43] found the cooling energy of a small office building located

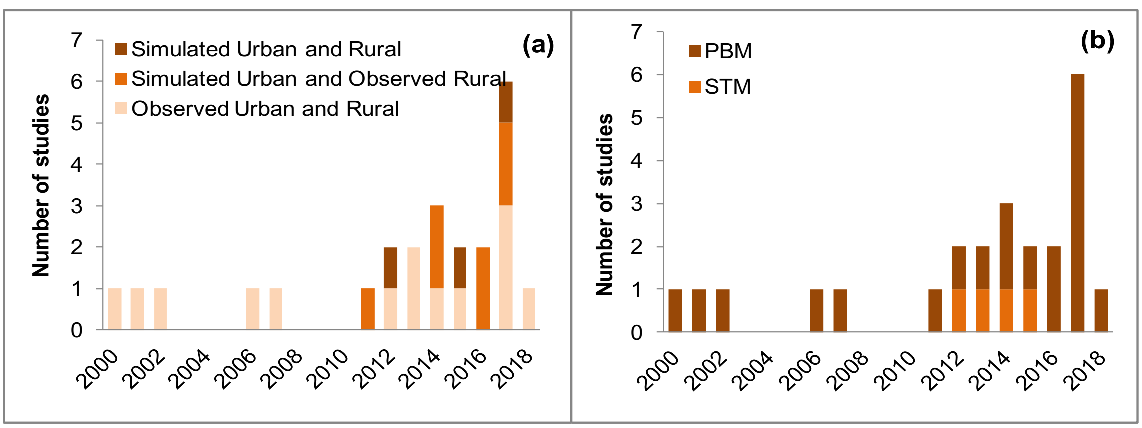

Fig. 2. Numbers of studies using different approaches for preparing temperature data with and without UHI effect (a) and using different approaches for estimating building energy consumption (b).

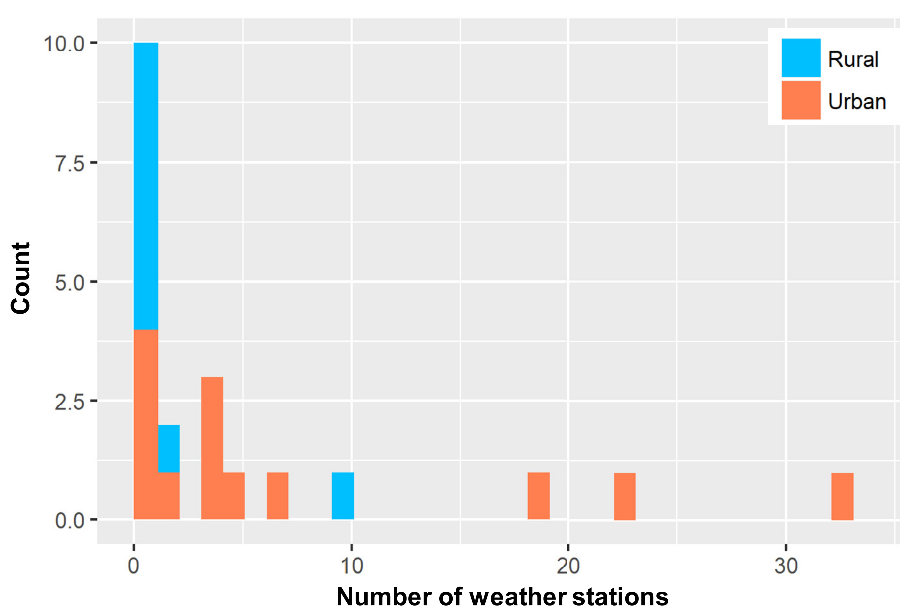

Fig. 3. Histogram of urban and rural weather station number used to investigate the UHI impacts on building energy consumption.

in the urban area of Boston, the U.S. was 22% and 42% higher compared to that located in two rural sites, respectively. Guattari et al. [44] found that the difference in the modeled UHI impacts on building energy consumption using temperatures from different rural stations could be as high as 50% in Rome, Italy. They also found that the selection of observation stations could even change the direction of the UHI impacts on building energy consumption with cooling and heating combined – the annual building energy consumption with cooling and heating combined increased by 1.7% in one case while it decreased by 7.2% in the other case [44]. It indicates that the modeled UHI impacts on building energy consumption are sensitive to the selection of rural stations and using the temperature from multiple rural stations could reduce the uncertainty [45].

Multiple urban stations were used in most studies to reveal the spatial variation of UHI within a city and intra-city variations of the UHI impacts on building energy consumption were reported in these studies (Table 1, Fig. 3). In Athens, air temperature data were collected from 33 urban stations when investigating the UHI impacts on building energy consumption [46]. In London, urban air temperatures from 19 stations were used to study the UHI impacts on building energy consumption [47–49]. Other studies used observation data from fewer urban stations, for example, 5 in Bahrain [50], 4 in Western Athens, Greece [51] and Rome, Italy [52], and 2 in Barcelona, Spain [27]. These studies without exception showed strong spatial variations of the UHI impacts on building energy consumption because of the spatial variation of UHI intensity.

The major advantage of using in-situ observed urban and rural temperatures is its easy access. Temperature data at the government-sponsored weather stations, such as the Global Historical Climatology Network-Daily (GHCN-Daily) dataset, are freely available [53,54]. However, the spatial coverage of these data is limited, and the spatial variations of the UHI impacts on building energy consumption cannot be captured well. In addition, these data may generate large uncertainty caused by the limited number of rural stations as discussed above. A possible solution is to spatially interpolate the in-situ observed air temperature to create gridded data with full spatial coverage [55]. The in-situ observed air temperature usually showed high inter-annual variations, and the UHI impacts on building energy consumption based on temperature in a single year may include uncertainties. One suggestion is to investigate the UHI impacts on building energy consumption based on the temperature of multiple years [51]. Another suggestion is to build typical meteorological year (TMY) data, representing the long-term typical climate [56,57], and then explore the UHI impacts on building energy consumption.

3.1.2. Simulated urban temperatures and observed rural temperatures

Instead of using the observed urban temperature, the simulated urban temperature with UHI effect was used in the second approach to study the UHI impacts on building energy consumption. Seven of the 24 studies used this approach and these studies were all conducted after 2010 (Fig. 2a). Generally two schemes were adopted to develop the UHI influenced urban temperature data. In the first scheme, independent data of UHI intensity can be first built and then assimilated with the UHI-free temperature data (e.g., the TMY without UHI effect [56–58]). Using the morphing method, Chan [59] produced the UHI-influenced temperature data based on TMY and UHI intensity calculated using temperatures at urban and rural stations and compared the building energy consumptions using these two temperatures (i.e., UHI-influenced temperature and TMY). Sun and Augenbroe [29] simulated UHI intensity using the Town Energy Budget model and the Interaction-Soil-Biosphere-Atmosphere model (TEB-ISBA) model, and the UHI intensity was then integrated with TMY to study the UHI impacts on building energy consumption of a typical office in 15 representative cities in the U.S.

In the second scheme, the urban temperatures were simulated directly based on the rural temperature and a series of urban morphology variables. Using an empirical statistical model [60], Ignatius et al. [61] and Liu et al. [62] estimated urban air temperatures for specific urban sites based on rural temperatures and a series of urban variables such as percent pavement, height to building area ratio, wall surface area, green plot ratio, and sky view factor. Palme et al. [42] created urban temperature data using the Urban Weather Generator tool based on metrics of four groups: (1) surface (e.g., albedo and emissivity), (2) buildings (e.g., internal gains, schedules of heating, ventilation, and air conditioning (HVAC) system, lighting, occupation, and efficiency), (3) urban geometry (e.g., built-up ratio, buildings' average height, and facade ratio), and (4) location (e.g., latitude and longitude). The generated urban temperature, together with the UHI-free rural temperature were then used to model the UHI impacts on building energy consumption.

This approach can generate UHI-influenced urban temperature in all urban areas, including urban center and urban periphery. Therefore, the UHI impacts on building energy consumption can be evaluated for all urban areas with a high spatial resolution. Since the UHI-influenced temperature was simulated based on urban morphology variables such as building density and greenspace coverage, this approach can be easily adapted to test the effectiveness of different urban planning strategies to mitigate energy consumption and emissions. However, this approach has several limitations. First, the models, specifically empirical models used to create the urban temperature data, are usually not widely available [60]. Second, the required high spatial resolution datasets of the urban morphology variables are usually difficult to acquire, especially for large areas, and therefore, previous applications of this approach mainly focused on some representative sites [29,42]. Moreover, the uncertainty similar to the first method still exists because the UHI-free background climate data in rural areas is still limited by the number of observation stations.

3.1.3. Simulated urban and rural temperatures

In the third approach, both UHI-free and UHI-influenced temperatures were simulated with a full spatial coverage using climate models. For example, Hirano and Fujita [63] simulated UHI-influenced and UHI-free temperatures based on the actual land use data and that with urban land replaced by natural land (i.e., an equally mixed land use of "forest" and "wasteland"), respectively. This approach has been widely used to study the impacts of urbanization on urban climate (i.e., UHI) [64–66], but it was rarely used to study the UHI impacts on building energy consumption. This approach was also used to study the UHI impacts on building energy demand caused by future urban expansion, based on the simulated present and future urban temperatures. Using this approach, Tewari et al. [36] modeled the impacts of the future urban expansion caused UHI on building energy demand in Arizona, U.S., in the context of climate change and rapid urbanization.

The simulated UHI-influenced and UHI-free temperature usually cover the entire city with a high spatial resolution. This full coverage datasets show the potential to explore the intra-city variation of UHI intensity and its impacts on building energy consumption. The major challenge of this approach is the scarcity of high spatial resolution auxiliary datasets required by climate models. In addition, it is computing intensive and time-consuming to prepare high spatial resolution gridded temperatures [67,68]. Therefore, the applications of this approach usually focus on a short period (e.g., a typical heat wave period [36,69]) or a single city [68,70]. These limitations could be solved with the rapid development of remote sensing technology (e.g., high spatial resolution remote sensing data) and data process capability (e.g., high performance computer).

3.2. Simulation/estimation of building energy consumption

Simulating/Estimating building energy consumptions with and without UHI effect is the second step to study the UHI impacts on building energy consumption. Bottom-up and top-down approaches have been developed to estimate or simulate building energy consumption at multiple scales [71–76]. The bottom-up approaches, including physics-based and empirical statistical modeling, were more widely used to estimate the UHI impacts on building energy consumption (Table 3). With a focus on the UHI impacts on building energy consumption, we briefly summarized the methods of building energy consumption estimation used for evaluating the UHI impacts on building energy consumption in previous studies (Table 3), because thorough reviews of current methods can be found in other papers [71,72,77–81].

3.2.1. Physics-based models

Physics-based models estimate building energy consumption following the thermal transfer principles based on the ambient temperature and physical characteristics of buildings, such as building geometry, HVAC systems, usage patterns, building envelope, thermostat set points, occupancy rates and schedules, and internal loads [11,71,72]. Though these models are complex and requiring a large number of physical parameters, the widely available software (Table 1 and other review papers [71,72]) makes it the most widely used method for evaluating the UHI impacts on building energy consumption. This approach was used in 20 of the 24 surveyed papers (Fig. 2b). EnergyPlus and TRNSYS were the most used software (Fig. 4 and Table 1).

The physics-based model is good at simulating building energy consumption at a local scale (e.g., a single building) with a high temporal resolution (e.g., minutes). Numerous input parameters are usually needed in the simulation. As the simulation can be conducted at each end use level with a high temporal resolution, such models could be used for evaluating the impacts of building characteristics, HVAC schedule, and others on the UHI impacts on building energy consumption. The most apparent disadvantage of the physics-based method is the availability of detailed building physical characteristics whose quality can influence the model performance [11,71,82]. As numerous simulations are usually needed for applications over large areas in practice, another limitation of this method is the requirement of intensive computation for large area studies [71,72]. A possible solution to these limitations is to develop reference buildings and group simulations based on climates, city characteristics, and building types [29,42].

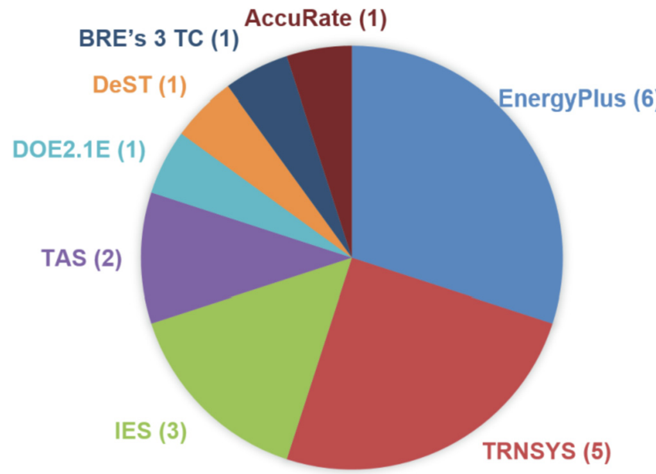

Fig. 4. Surveyed physics-based softwares or models for evaluating the UHI impacts on building energy consumption. The values are the number of applications.

3.2.2. Statistical models

The statistical model is another method to estimate building energy consumption when studying the UHI impacts on building energy consumption [75,83]. These models were developed based on the empirical statistical relationship between surveyed building energy consumption and ambient temperature. These models have been developed at multiple spatial scales from the building level [84] to the city [85,86] and the national level [87,88], depending on the availability of energy consumption data. However, the surveyed building energy consumption datasets are usually not widely available and only four of the 24 studies used this method (Table 1). Hirano and Fujita [63] found a strong correlation between building energy consumption (i.e., space cooling and space heating) and ambient temperature with R^2 higher than 0.94 and built 648 estimation equations to quantify the UHI impacts on building energy consumption in Tokyo, Japan. In another two studies, linear regression models with R^2 between 0.76 and 0.89 were developed to investigate the domestic electricity consumption and the increase in electricity consumption of air-conditioning caused by the UHI effect in the hot arid region, Bahrain [50,89]. Li et al. [90] built a logistic model with a R^2 of 0.9 to estimate building energy consumption of electric air-conditioning and the UHI impacts on building energy consumption in Beijing, China.

The statistical model is relatively easy to be implemented as it requires fewer inputs compared to the physics-based model. Temperature data (e.g., temperature or cooling/heating degree days) is the key parameter in these models [50,63,89,90]. Moreover, this approach is good at modeling the impacts of exogenous factors (e.g., economic factors and climate) on building energy consumption. However, such statistical models were usually developed at

Table 3
Advantages and disadvantages of two widely used approaches for estimating building energy consumption, adapted from Refs. [71,80].

Approaches	Advantages	Disadvantages
Physics-based model	➢ Deterministic based on building physics ➢ Building level simulation ➢ Simulation of multiple end uses ➢ Very high temporal resolution ➢ Suitable for testing the impacts of building characteristics, cooling technologies, etc.	➢ Require detailed building characteristic data ➢ Hard to upscale to the city or higher level ➢ Hard to calculate and time-consuming ➢ Hard to model the impacts of socioeconomic factors
Statistical model	➢ Empirical-based on real time data ➢ Easy calculation ➢ Usually applied for the city or higher level ➢ Evaluate the impacts of exogenous factors (e.g., economic factor)	➢ Require past records of energy data ➢ Black box of the energy process. ➢ Difficult in modeling different end uses ➢ Coarse resolution in space and time

the aggregate levels (e.g., city, province/state, and national), which could not capture the spatiotemporal variation of the relationship between building energy consumption and ambient temperature. The geographically weighted regression model using large samples of building level energy consumption could be a possible solution to this problem. Additionally, it is difficult to evaluate the UHI impacts on building energy consumption with the consideration of changes in endogenous factors (e.g., building characteristics). This question could be well answered by the physics-based model.

3.3. Comparing building energy consumption with and without UHI effect

Comparing the estimated building energy consumptions with and without UHI effect is the last step to evaluate the UHI impacts on building energy consumption. The results are usually expressed as percentage change of building energy consumption with UHI effect compared to that without UHI effect.

4. Findings of UHI impacts on building energy consumption

4.1. Building cooling energy consumption

Based on the published cases studies (Table 1), UHI, could increase building cooling energy consumption by a median of 19% with great variation, ranging from 10% to 120% globally (Fig. 5). The global median increase of the building cooling energy consumption is slightly higher than the average of the modeled impacts in 15 U.S. cities (17.25%) [29] and the estimated global average impacts (13%) [31]. There were strong spatial variations in (1) the number of samples and (2) the estimated median value of the UHI impact on building energy consumption across regions (Fig. 6a). The reported UHI impacts on building cooling energy consumption did not show a clear geographical pattern and a relationship with the development stage of the city (Fig. 5a). It could be mainly caused by the significant differences in the input datasets (e.g., temperature), the methods for quantifying UHI intensity and estimating building energy consumption, the spatiotemporal scales (e.g., the single building or whole city) (Table 1).

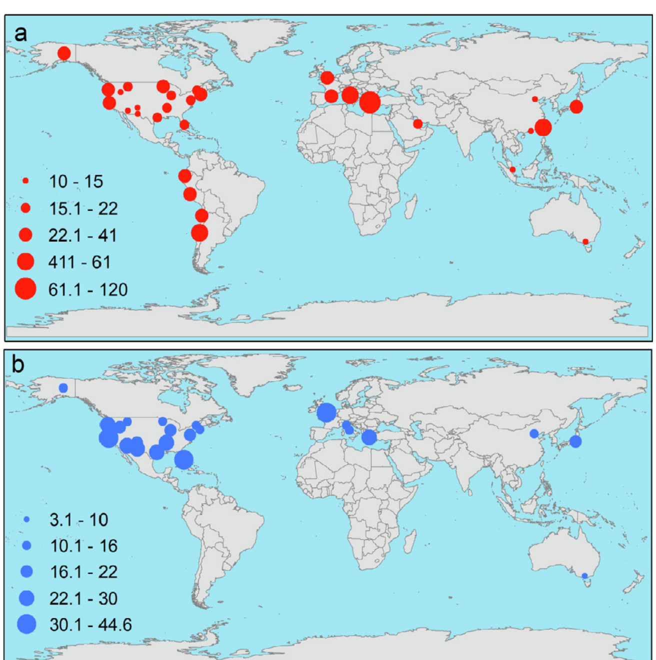

Fig. 5. Percentage increase in building cooling energy consumption (a) and percentage decrease in building heating energy consumption (b) by UHI. (Note: The circles are overlapped for some cities with multiple studies.)

There are clear intra-city variations of the UHI impacts on building cooling energy consumption. The strongest impacts usually occurred in the urban center and the weakest impacts occurred in urban periphery, generally consistent to the intra-city pattern of the UHI intensity. In the western Greater Athens, Greece, Hassid et al. [51] found that the urbanized area showed a 15–50% higher cooling load and a 30–80% higher maximum electrical cooling load depending on the location of urban sites. Based on the observation data from 26 stations, Santamouris et al. [46] mapped the isolines of the building cooling energy consumption of a typical building in the city of Athens. The building cooling energy consumption decreased gradually from urban center to urban periphery. The intra-city variation of the UHI impacts on building cooling energy consumption was also reported by the simulated building energy consumptions of 24 sites in London [47,48]. Building cooling energy consumption increased 2%–10% for four different urban sites compared to the rural sites in Bahrain [50]. In Rome, Italy, the increase in building cooling energy consumption varied between 12% in the peripheral neighborhood and 46% in the city center [52]. Similar findings were also reported based on the simulated urban temperature [29]. For example, by modeling UHI intensity of 58 situations (sites) with different urban geometric parameters including (1) canyon height, (2) canyon aspect ratio, (3) coverage of vegetation, and (4) coverage of building, Sun and Augenbroe [29] found higher UHI impacts on building cooling energy consumption in large city centers than that in other urban areas. Based on the simulated UHI and TMY, the UHI impacts on building cooling energy consumption for a typical office building in Singapore were calculated and the impacts ranged between 4% and 12% [61,62].

The UHI impacts on building cooling energy consumption varied among different building types. The study in Hong Kong, China showed different UHI impacts between office buildings and residential buildings for both magnitude and temporal pattern [59]. Specifically, during a hot month (i.e., July), UHI showed stronger impacts for office buildings, while during a mild month (e.g., May and October), residential buildings were more affected by UHI. A study in Boston, U.S., reported stronger UHI impacts on building cooling energy consumption for office buildings than that for residential buildings [43]. At the city level in Tokyo, Japan, UHI caused a higher absolute increase in building cooling energy consumption for the commercial sector than the residential sector [63]. The simulations in four South American cities showed variations of the UHI impacts on building cooling energy consumption for different types of residential buildings with the highest relative increase for the detached family, followed by the medium-sized block of apartments and tall buildings [42]. Nevertheless, Skelhorn et al. [28] found that the increases in building cooling energy consumption by UHI in three residential buildings with different height, floor area, and layout were close, with a difference lower than 3% in Manchester, UK.

Improvement in building thermal insulation can significantly reduce the UHI impacts on building cooling energy consumption. Guattari et al. [44] found that the UHI impacts on building cooling energy consumption for a residential building varied with building envelope designs and technologies (18%–41%). Zinzi and Carnielo [52] found that the thermal insulation of the building envelope reduced the UHI impacts on residential building cooling energy consumption in Rome, Italy. However, the study in Modena, Italy did not report significant influences on the modeled UHI impacts by applying the cool coating of roof and opaque vertical surfaces in a university library [91]. This may indicate that the thermal

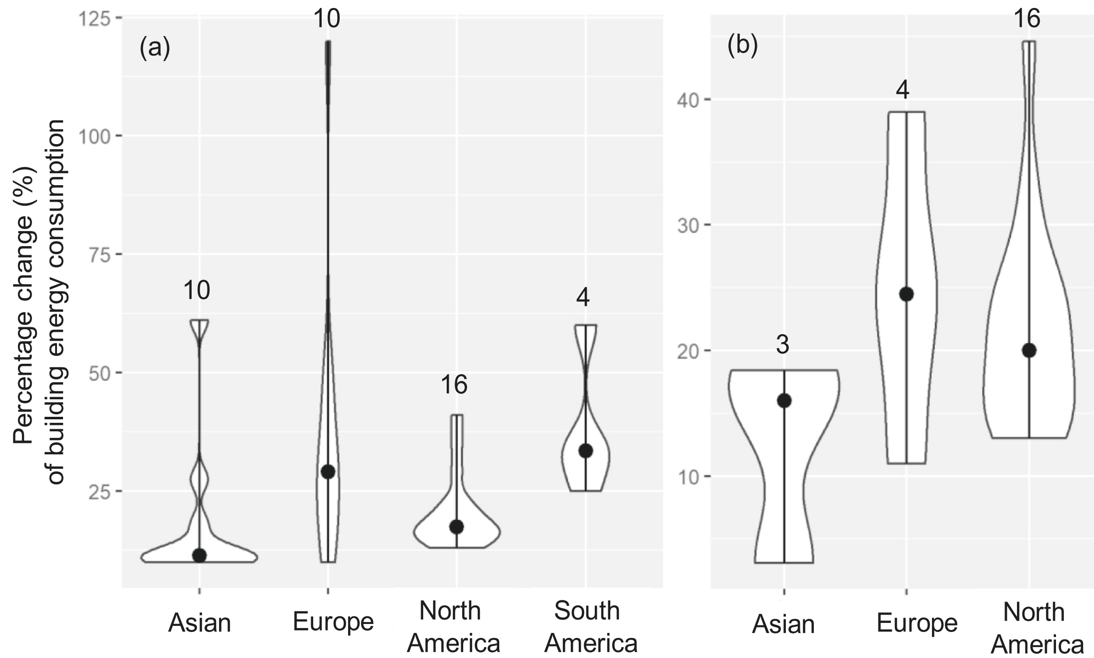

Fig. 6. Percentage increase in building cooling energy consumption (a) and percentage decrease in building heating energy consumption (b) caused by UHI at the regional level. The point indicates median value and the number indicates number of samples. There is no study of UHI impacts on building heating consumption in South America.

insulation may play different roles in affecting the UHI impacts on building cooling energy consumption in different building types, but further studies are needed for an improved understanding.

As building cooling energy is mainly used for air conditioning, the set point of cooling is expected to be highly relevant to the UHI impacts on building cooling energy consumption. An increase in the set point decreases the modeled building cooling energy consumption, but results in an increase of the UHI impacts on building cooling energy consumption. The UHI impacts on the residential building cooling energy consumption was raised from 55% with a set point of 24 °C to 82% with a set point of 27 °C in Athens, Greece [51]. Another study in the same city of Athens showed that the UHI impacts on building cooling energy consumption doubled with the set point increasing from 26 °C to 28 °C [46]. The study in Barcelona, Spain showed that the relative increase in building cooling energy consumption caused by UHI grew with the increase of set point, especially on a hot day [27]. The increase of the UHI impacts on building cooling energy consumption with the increase of set point is mainly caused by the significant decrease of cooling energy consumption in the rural area (i.e., the reference case without the UHI effect).

4.2. Building heating energy consumption

There are fewer (10 of 24) studies about the UHI impacts on building heating energy consumption (Table 1). These studies showed a consistent decrease in building heating energy consumption caused by UHI, with a median decrease of 18.7% and a range of 3%–44.6%, globally (Fig. 5b). Similarly, the UHI impact on building heating energy consumption for cities at the global (Fig. 5b) and regional levels (Fig. 6b) did not show a clear relationship with the development level for the reasons discussed above (i.e., the difference of input datasets (e.g., temperature), methods for quantifying UHI intensity and estimating building energy consumption, and the spatiotemporal scales). However, the results in the U.S. showed a latitude gradient, namely, UHI caused a higher decrease of building heating energy consumption in higher latitude areas [29]. This is possibly because the demands for heating is lower in the South with a warmer temperature compared to the north and a small decrease of heating energy consumption can result in a large relative change. Within city, the UHI impacts on building heating energy consumption showed a clear urban-rural gradient with a higher relative decrease in the urban center because of the higher UHI intensity [49].

4.3. Building energy consumption with cooling and heating combined

10 of the 24 studies reported the UHI impacts on building energy consumption with cooling and heating combined (Table 1). Since building cooling and heating energy consumptions respond to temperature increases in opposite directions, the UHI impacts on building energy consumption with cooling and heating combined varied spatially, depending on which component plays a dominant role. The simulation of a typical office in 15 representative cities across different climate zones in the U.S. showed that building energy consumption with cooling and heating combined will increase in cooling dominated regions but decrease in heating dominated regions caused by UHI [29]. In addition, the UHI impacts on building energy consumption with cooling and heating combined varied between residential and commercial building sectors. The study in Boston, U.S. showed a larger decrease of building energy consumption with cooling and heating combined in residential buildings than that in office buildings [43]. In Tokyo, Japan, UHI increased building energy consumption with cooling and heating combined by 1% in the commercial sector but decreased building energy consumption with cooling and heating combined by 8% in the residential sector at the city level [63].

5. Challenges and future research

Previous studies have reported spatial patterns of the UHI impacts on building energy consumption, with the highest impacts in the urban center and decreasing impacts from the urban center to the urban periphery. However, such spatial patterns were mainly discovered based on a limited number of selected sites and few studies reported the detail of spatial variations in the UHI impacts, mainly due to the data unavailability. Though some geostatistical technologies can be used to spatially interpolate the UHI impacts on building energy consumption from selected sites to the whole city, the spatial detail is still limited in a smooth surface of the UHI impacts [46]. High spatial resolution gridded air temperature datasets with a spatial coverage in both urban and rural areas, instead of the in-situ observed air temperature, can greatly improve the investigation of spatial patterns of the UHI impacts on building energy consumption. Simulating high spatial resolution gridded air temperature using climate models such as the study of Hirano and Fujita [63] is a potential method and the newly created high spatial resolution gridded air temperature dataset [38,55,92,93] is another potential method.

Though studies were conducted in many cities around the world as shown in Fig. 5, it is difficult to compare the results among different studies because these studies varied greatly in many factors such as geographical locations, study periods, background climates, UHI definition and calculation, the method of building energy consumption estimation, and building characteristics. Sun and Augenbroe [29] compared the UHI impacts on energy consumption of a typical office building in 15 representative cities in different climate zones in the U.S. and Palme et al. [42] simulated the UHI impacts on energy consumption of residential buildings in four South American Pacific coastal cities. Such comparative studies can be extended to other regions and even global to improve the understanding of the UHI impacts on building energy consumption (e.g., regional and global patterns and relationship with city characteristics such as geographical locations, sizes, development stages). Given the complexity and large variations of the impacts, international and inter-city comparison projects are suggested. Standards such as modeling datasets, model setup (e.g., set points), and reference building for different types, can be designed in these projects. In addition, with comparable results, the relationship between the UHI impacts on building energy consumption and UHI magnitude and background climate can be investigated [31].

Studies of UHI impacts on building energy consumption showed an uneven spatial distribution with most of them in North America and Europe, but few of them in Africa, Asia, and South America (Fig. 5). The possible reasons are: (1) UHI has a smaller spatial extent in developing countries as their urbanization level is still low; (2) UHI impacts were not paid enough attention in developing countries as the governments focused more on socioeconomic development instead of the environment; and (3) The required data (including temperature and building characteristic) for studying the UHI impacts on building energy consumption are scarcer in developing countries. Considering the rapid socioeconomic development and urbanization in Asia and Africa [94,95], it is expected that there will be a significant increase in building energy consumption and UHI intensity. Investigating the UHI impacts on building energy consumption in these developing regions should be highlighted in the future.

Previous studies mostly evaluated the UHI impacts on building energy consumption by a spatial comparison using historical temperature data, but fewer studies investigated the UHI impacts in a warmer future influenced simultaneously by the global climate change and the increase of local UHI intensity caused by further urban expansion. Kolokotroni et al. [49] compared building energy consumption of an office building with the location moved from rural to urban areas and from the present (2010) to 2050 in London under a future climate change scenario. Hwang et al. [17] compared building energy consumptions for a typical residential apartment in rural and urban areas of central Taiwan, China in a future period of 2075–2099. However, both studies did not consider the increased UHI intensity due to future urban expansion. A simulation study in Arizona, U.S. even showed that the impacts of urban expansion on building energy consumption were higher than that of global climate change [36]. Investigation of the UHI impacts caused by urban expansion on building energy consumption in the context of global climate change is highly recommended especially in regions with an expected high urban expansion. This also alerts us that in addition to the global climate change, the local urban warming caused by urban expansion should be explicitly incorporated in climate modeling and projection.

6. Conclusions

Although the significance of the UHI impacts on building energy consumption is widely recognized by the scientific and policy communities, the quantitative UHI impacts are understudied. In this study, we reviewed literature that quantitatively modeled UHI impacts on building energy consumption. A majority of previous studies investigated UHI impacts for a typical building using temperatures from urban and rural sites based on physics-based models, and a few studies investigated the spatial (both intra- and inter- city) variations of the UHI impacts. We found UHI could lead to a median of 19% increase in building cooling energy consumption and a median of 18.7% decrease in building heating energy consumption. Moreover, the reported UHI impacts showed strong intercity variations with an increase of cooling energy consumption ranging from 10% to 120% and a decrease of heating energy consumption ranging from 3% to 45%. Within a city, the UHI impacts were found the highest in the urban center and showed a decreasing urban-rural trend, similar to that of UHI intensity.

The major challenge in evaluating UHI impacts is the scarcity of data with high spatial resolutions and a large spatial coverage, such as temperature data with and without UHI effect and building data with detailed characteristics. These limitations are expected to be partially addressed in future studies with better temperature data (e.g., the newly created high spatial resolution air temperature datasets [55,92]) and reference buildings of different types in a variety of climate zones. In addition, previous studies were mainly conducted in developed countries (e.g., in North America and Europe) from the spatial perspective (i.e., urban and rural comparisons), while the rapid urban expansion, with a resulting increase in UHI intensity, is expected in developing countries in the coming decades. More attention can be paid in future studies for the UHI impacts on building energy consumption in developing countries (e.g., in Asia and Africa). In addition, investigating UHI impacts on building energy consumption in the context of combined future climate change and urbanization is recommended in future studies.

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