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Impacts of urbanization and air pollution on building energy demands — Beijing case study

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HIGHLIGHTS

- A comprehensive model validation is conducted for the coupled building energy model.
- The modeled building energy demand agrees well with observation and EnergyPlus.
- Urban heat island increases/decreases cooling/heating energy demand in urban Beijing.
- There exits an impact-chain of air pollution-urban heat island-heating energy use.

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ABSTRACT

This article addresses the nexus of intense urbanization, building energy and air pollution, a topic minimally explored in the literature. The urban heat island effect on building energy demands for cooling and heating is investigated for Beijing through observations and modeling with a coupled Building Effect Parameterization-Building Energy Model and a single building energy model. The average urban heat island intensity in Beijing during summer is approximately 2.02 K, and in winter, this value reaches 3.41 K. The models used for the investigation are forced with observations from two meteorological towers, one located in downtown and the other in the outskirt. Model validation is conducted for environmental variables and for building energy demands against surface weather observations and actual electricity data, showing good agreement in all cases. Results for a 6-storey office building indicate that cooling energy use in the urban area is 36.53 W m^{-2} (30%) higher than the suburban area during summer, while heating energy use is 95.29 W m^{-2} (23%) lower than the suburbs during winter. Residential building shows similar results, with smaller differences in cooling and heating energy use, about 9.14 W m^{-2} (17%) and 92.71 W m^{-2} (20%), respectively. Analysis of clear and polluted winter days shows the impact-chain of air pollution – urban heat island – heating energy use. Heating energy demand is reduced in the urban area during polluted days, corresponding to an enhanced heat island, which may be attributed to a stronger inversion and a lower wind speed.

1. Introduction

According to the newly-revised world urbanization prospects [1], about 54% of the world's population resided in urban areas by 2014, and this figure is projected to be 66% by 2050. Progressive replacement of natural land cover by built-up surfaces results in more effective heat storage in urban areas, leading to the formation of the urban heat island (UHI), a well-documented phenomenon where city centers are routinely warmer than surrounding areas [2–4].

As demonstrated in many studies [5–9], anthropogenic heat from buildings and vehicles plays a very important role in further exacerbating UHI. For example, waste heat from air conditioners (AC) was found to cause a temperature rise of 1–2 °C or more, increasing UHI magnitude in Tokyo office areas during summer weekdays [5,6]. For a semiarid urban environment like the city of Phoenix in the United States (US), waste heat release from AC systems increased the nighttime mean 2-m air temperature by over 1 °C in some urban locations, strengthening the nocturnal UHI and increasing cooling demands [7,8]. It has also been shown that anthropogenic heating affects surface air temperature more strongly than a larger heat capacity and a smaller

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Nomenclature

E_C/E_H	cooling/heating energy demand (W)
Q_{AC}/Q_{AH}	waste heat released by the cooling/heating systems (W)
H_{in}/E_{in}	sensible/latent heat load in one building (W)
H_{out}/E_{out}	sensible/latent heat extracted or added by the cooling/heating systems (W)
H_{loss}	heat loss from buildings in winter (W)
COP/eff	coefficient-of-performance/Efficiency for the cooling/heating systems
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
C	heat capacity ($J\ m^{-3}\ K^{-1}$)
ε/α	surface emissivity/albedo
Z_0	roughness length over the surface (m)
Q^*	net radiation flux ($W\ m^{-2}$)
T_{2m}/T_{init}	2-m air temperature/Initial temperature of the surface (K)
q	near surface specific humidity ($g\ kg^{-1}$)
WS_{10m}	10-m wind speed ($m\ s^{-1}$)

sky-view factor [9].

The above indicates that there exists a positive feedback cycle between UHI and anthropogenic heat from buildings in summer [10]. Waste heat release due to air conditioners causes an increase in urban air temperatures, leading to a strengthened UHI, which further increases cooling energy demand and waste heat emissions. However, in winter, this positive feedback is reversed; the UHI decreases heating energy consumption in cities, a fact that may have been overlooked in past studies [11]. Thus, additional work is needed to quantify the UHI effect on the year-round building energy use for megacities such as Beijing, where the highest daily energy load was approximately 19,100 MW, 40% of which was due to AC use in summer 2011 (http://zhengwu.beijing.gov.cn/gzdt/gggs/t1190167.htm). Besides, emerging megacities pose additional challenges to air pollution, e.g., combustion of hydrocarbon fuels in residential areas, vehicular exhausts due to traffic, and UHI-associated mesoscale flow plays an important role in shaping the urban pollution pattern, resulting in positive or negative feedbacks on energy demands of the built environment, a subject minimally investigated.

UHI impacts on energy demands have been evaluated for many cities with statistical methods [10–16] or numerical simulations [17–24]. Linear regression equations were developed to assess the role of higher temperatures in the variation of Bahrain's domestic electricity consumption for air-conditioning, using cooling degree days (CDD) as a quantitative index, with results showing that annual total CDD value was up to 17% higher than rural [12]. A similar regression method was adopted in Beijing [10] and Tokyo [11]. Another statistical technique is artificial neutral network, which requires a series of historic measurements for air temperatures within the city [13,14]. In terms of degree days, summer cooling demand was approximately 25% higher and heating demand was 6% lower in downtown Madison compared to its rural surroundings [15]. The similar degree-day method was also used for Athens [16]. Although statistical analysis for prediction of cooling energy consumption may be an effective tool under limited conditions, numerical simulations show a particular advantage in exploring physical processes and feedbacks between natural and built environments, especially in the absence of sufficient measurements for energy use.

Given this, numerical models have been employed in some studies to assess the energy impacts of UHI for different cities, e.g., Athens [17,18], London [19], Barcelona [20], Milan [21] and Beijing [22]. Based on twenty weather files that were constructed in an East-West axis through London, a single building thermal simulation program was used to simulate the energy consumption for cooling and heating of an office building, and results confirmed that, while heating load decreased, cooling load and overheating hours increased as the office location moved from rural to urban sites and from present to future years, which reflected London UHI's role in energy demands [19]. In order to cover different climate zones across the US [23], EnergyPlus, a single building energy model [25,26], was employed, and respectively driven by rural typical meteorological year weather data and modified ones based on hourly UHI magnitudes in various urban environments, which were generated from the Town Energy Budget [27]. Consequently, ignoring the UHI effect remarkably underestimated building total energy use in hot climate zones, yet caused overestimation in cold climate zones, and in mild climate zones, the effects on cooling and heating mostly averaged out [23]. Both of the above studies [19,23] considered UHI and building energy simulation with relative independence, not considering the thermal interaction between outside

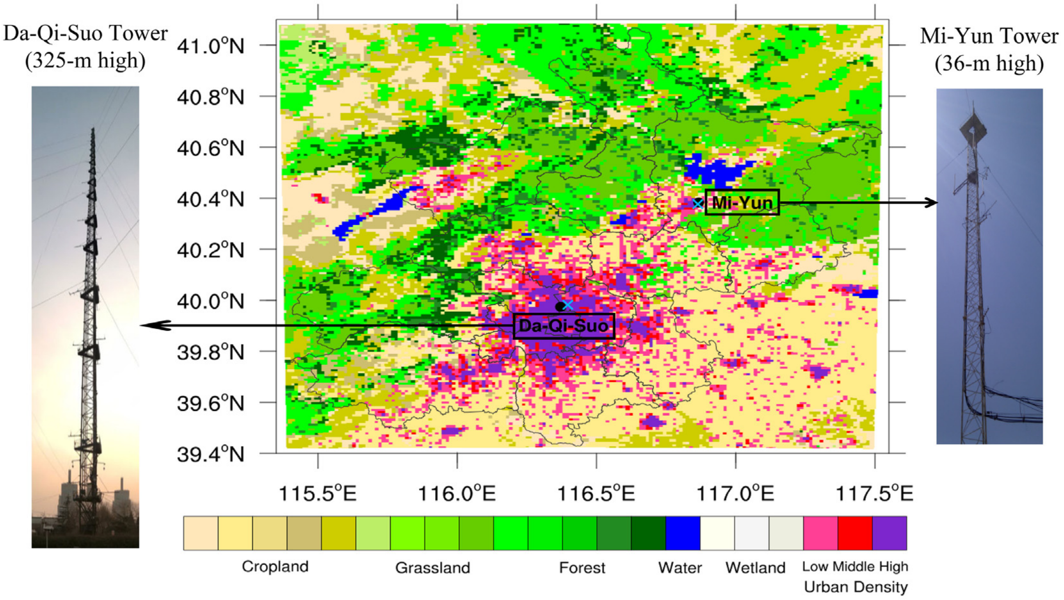

Fig. 1. Locations of two meteorological towers (black dot) and the nearest AWS sites (sky-blue cross) in the context of urban land classes (the color scale, 1-km gridded). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)