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Spatiotemporal characteristics of anthropogenic heat in an urban environment: A case study of Tsinghua Campus

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ABSTRACT

In this study, a detailed investigation of the spatiotemporal characteristics of anthropogenic heat (AH) from different sectors (i.e. human metabolism, transportation and building energy consumption) in an urban environment (the Tsinghua Campus in Beijing, China) is conducted using inventory and building energy modeling methods. The AH is estimated as large as 220.0 W m^{-2} (at about local time 7pm) in summer and 221.0 W m^{-2} (at about local time 6am) in winter. The results indicate that AH on Tsinghua Campus (TC) displays clear diurnal and seasonal cycles. Among the three sectors on TC, building energy consumption contributes the most to the total AH (about 97.4%), whereas metabolism and transportation accounts for 1.4% and 1.2% respectively. The spatial distribution of AH on TC indicates that higher AH is generally observed in more densely built-up areas with the hourly maximum value of 474.3 W m^{-2}. Comparison between AH and incoming solar radiation shows that the magnitude of AH is about 43% and 92% of the incoming solar radiation in summer and winter, respectively. Therefore, AH should be considered as an important component of the urban representation in numeric weather prediction models and should be carefully accounted for when considering the urban surface energy balance. This study provides evidence of the significance of AH in urban environment and suggestions for improvement of urban module in numeric weather prediction models.

1. Introduction

Despite that urban areas only cover 0.5% of Earth's land [1], more than half of the world's population live in cities. With worldwide continuously increasing urbanization, it is projected that more and more people will move into urban environments. The surface energy balance is a key to understand urban environmental issues and can be described as follows:

$$R_n + Q_F = H + LE + Q_S + Q_A \tag{1}$$

where R_n is net radiation, Q_F is the value of AH, H is sensible heat, LE is latent heat, Q_S is heat storage and Q_A is advective heat. The left-hand side of Eqn. (1) denotes the available energy, whereas the right-hand side (RHS) is the dissipation of available energy through turbulent transport (i.e. H and LE), conduction (i.e. Q_S) and advection (i.e. Q_A). Among the terms in Eqn. (1), the anthropogenic heat (Q_F), which primarily consists of emissions from human metabolism, industry, transportation and buildings [2], is considered as an important contributor to the available energy in urban environments but is usually not carefully accounted for. Offerle et al. [3] found that the anthropogenic heat (AH) can contribute 60% of available energy with an average of 32 W m^{-2} from October to March over 2001–2002 in Łódź, Poland. Comparison against the net shortwave radiation indicates that the AH from buildings in London could be 3–25 times greater than the net shortwave radiation during a winter day [4]. In addition, AH has a significant impact on urban climate. For instance, AH is widely recognized to be one of the major factors causing the urban heat island effect [5]. Tong et al. [6] estimated an hourly maximum Q_F value around 200 W m^{-2} in Beijing, which may result in a temperature increase of about 0.5 °C in the daytime and 1–3 °C at night. Ichinose et al. [7] found that AH emissions led to an increase of nocturnal air temperature about 2–3 °C in winter and 1.5 °C in summer in Tokyo. Due to the significance of AH in understanding the urban surface energy balance and the urban climate, different approaches have been proposed to estimate AH at different temporal scales [2]. These approaches can be categorized into inventory, energy budget closure, and building energy modeling methods:

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(1) The inventory method is a widely used approach for its easy data accessibility and straightforward concept [2]. The earliest results by the inventory method show that the mean annual value of AH is around 83.7 W m^{-2} in US urban areas [8]. The accuracy of this method largely depends on the availability and the quality of data and this method typically quantifies AH at relatively coarse spatial and temporal scales.

(2) The energy budget closure method estimates AH through Eqn. (1) by measuring or modeling the other terms. It has been used in different cities (see e.g. Europe [3], North America [9] and Japan [10]). Nevertheless, accurate estimate of the other terms in Eqn. (1) remains to be difficult due to the uncertainty in measurements and the inherent surface energy closure problem [11] even for flat and homogeneous surfaces, which thus restrains the application of this method for estimating AH.

(3) The building energy modeling method is usually employed to obtain the building energy consumption (BEC) in densely built-up areas. The basis of this method lies on the assumption that the building sector accounts for the largest fraction of the total anthropogenic heat (e.g. the building sector contributes to 40% of total energy consumption [12] in the US). Several building energy models have been developed and applied in different cities to estimate AH (see e.g. DOE in Tokyo [13,14], eQUEST in the US [15], EnergyPlus in Taipei [16], eQUEST in Houston TX [17]).

Using these approaches, several studies investigated the characteristics of AH at various spatiotemporal scales and their results are summarized in Table 1. It is found that as the spatial resolution of the area of interest (AOI) becomes finer, the magnitude of AH increases and accounts for a larger proportion of the available energy. At global scales, Allen et al. [18] found that the global mean urban AH has a diurnal range of 0.7–3.6 W m^{-2} using a global model LUCY (**L**arge scale **U**rban **C**onsumption of energ**Y**). Similar work at city scales by Flanner [19] found that AH of major US cities ranges between 20 and 40 W m^{-2} in summer and between 70 and 210 W m^{-2} in winter [5]. At building-block scales, Ichinose et al. [7] found that Q_F in Tokyo could be as large as 1590 W m^{-2} in winter and more than 400 W m^{-2} in summer. Iamarino et al. [20] found the daytime AH could reach to 550 W m^{-2} in the city of London at a resolution of 200 m. Similar results by Sailor and Lu from several US cities [21] also indicate the magnitude of AH from the urban core areas can be as 5–10 times high as that averaged over the whole city. In terms of the temporal characteristics of AH, several studies [21–23] found that the diurnal cycle of AH peaks in the morning and evening, which is consistent with the diurnal pattern of human activities.

Meanwhile, growing concerns on urban climate requires development of more realistic urban representation in numeric weather prediction (NWP) models (for e.g. the Weather Research and Forecasting model [24] etc.). It is now gradually recognized that, in addition to the static parameters (i.e. the morphological [25,26] and material properties [27,28]), AH is an important, dynamic element that should be included in urban representations. However, current AH data used in NWP models usually have a large uncertainty. In addition, AH may vary significantly across cities and thus should be implemented in NWP models based on a city-specific investigation of its characteristics. A step toward improving the representation of AH in NWP models is to quantify the importance of AH, as compared to the other terms in Eqn. (1), at relatively larger spatial scales (on the order of a few kilometers, which are typical resolutions of NWP models). As such, the objective of this study is to provide a detailed investigation of spatiotemporal characteristics of AH in a moderately urbanized area.

In addition, considering the applicability of different estimating methods, an ensemble approach consisting of different methods for various sectors is introduced in this study to provide a more detailed estimate of AH, which is a novel work and could be generally applied to other urban environment at the same scale. We choose a university campus as AOI of this study due to the feasibility for conducting inventory survey. In the rest of this paper, we start by describing the AOI and the ensemble approach for estimating AH, followed by the estimated AH from different sectors and its spatiotemporal characteristics. Based on the estimates, the magnitudal-temporal comparison between AH and incoming solar radiation is conducted to assess the significance of AH to urban atmospheric environment.

Table 1
Characteristics summary of anthropogenic heat in different cities.

Country	City	Year	Approach	Q_F (W m^{-2})			Reference
				Annual	Summer	Winter	
US	Major Cities	1959–1971	I	83.7^{b}	–	–	Torrance and Shum (1976) [8]
	Major Cities	2000	I	–	30–60^{b}	70–75^{b}	Sailor and Lu (2004) [21]
	Major Cities	2002	I	–	0.7–96.3^{a}	0.5–69.4^{a}	Sailor and Hart (2004) [22]
	Houston TX	2003	B	–	320^{a}		Sailor et al. (2007) [17]
	Houston TX	2002	B	–	100^{a}	117^{a}	Heiple and Sailor (2008) [15]
Japan	Tokyo	1989	I	–	908^{a}	1590^{a}	Ichinose (1999) [7]
	Tokyo (Residential area)	2003	B	–	150^{a}	–	Dhakal et al. (2003) [13]
	Tokyo (Commercial area)	2004	B	–	114^{a}	–	Dhakal et al. (2004) [14]
	Nagoya	2000	E	–	197^{b}	117^{b}	Kato and Yamaguchi (2005) [10]
	Tokyo	1986–1994	I	284^{a}	–	–	Moriwaki et al. (2008) [39]
	Tokyo (Commercial area)	1998–2001	I	220^{a}	–	–	Kikegawa et al. (2013) [40]
Poland	Lodz	1984–1986	I	29^{b}	12^{b}	54^{b}	Klysik (1996) [41]
	Lodz	2001–2002	E	–	−3^{b}	32^{b}	Offerle et al. (2005) [3]
UK	London (Commercial area)	2005	I	9^{b}	230^{a}	530^{a}	Hamilton et al. (2008) [4]
Singapore	Commercial area	2008–2009	I	–	320^{a}	–	Quah and Roth (2012) [23]
China	Beijing	2000	I	–	–	200^{a}	Tong et al. (2004) [6]
	Beijing (Peking Campus)	2006	B	–	84.4^{a}	–	Yu et al. (2014) [42]
	Beijing (Tsinghua Campus)	2005–2012	I, B	–	257.3^{a}	268.1^{a}	This study

I: Inventory method; E: Energy budget closure method; B: Building energy modeling method.
[a] The maximum hourly-averaged value.
[b] The mean hourly-averaged value.