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A distributed model for quantifying temporal-spatial patterns of anthropogenic heat based on energy consumption

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A B S T R A C T

Although energy-induced anthropogenic heat emissions form localized hotspots, they can influence the variability of urban climate. A lack of anthropogenic heat quantification in different locations and times has created a barrier in current research on urban climate. This study presented a distributed model of anthropogenic heat (DMA) that can be used for quantifying the temporal-spatial patterns of anthropogenic heat. The intensity of anthropogenic heat was estimated by separately considering the major sources of waste heat generated in urban environments from vehicular traffic, buildings, industry, and human metabolism individually. The contribution of anthropogenic heat to urban environments was assessed by the ratio of anthropogenic heat intensity to solar radiation (δ). The DMA was implemented inside the 5th ring-road of Beijing based on 6941 urban functional zone polygons which were attributed to seven zone types including agricultural, campus, commercial, industrial, preservation, public, and residential. Results showed that: (1) the total anthropogenic heat in Beijing reached 1.11×10^{18} J per year. Buildings occupied 45% of the total anthropogenic heat fluxes, followed by traffic (30%), industrial (20%), and human metabolism sources (5%); (2) the mean intensity of anthropogenic heat peaked at 135 Wm^{-2} in winter, 84 Wm^{-2} in autumn, 82 Wm^{-2} in summer, and 77 Wm^{-2} in spring; (3) the contribution of anthropogenic heat to urban climate decreased in the order of commercial ($\delta = 0.5$), industrial (0.47), campus (0.33), residential (0.32), public (0.32), preservation (0.09), and agricultural zones (0.07). This study indicates that a greater focus on energy reduction would be most effective in mitigating the effects of anthropogenic heat in commercial and industrial zones and in winter. The DMA is a feasible tool that can be used to quantify the temporal and spatial variations of anthropogenic heat based on energy consumption data in other urban regions.

1. Introduction

The percentage of the world's population living in urban areas is increasing rapidly and, by 2050, is expected to reach nearly 70% (United Nations, 2010; McDonald et al., 2016). Rapid urbanization leads to great energy consumption and significant landscape transformation in metropolitan regions (Georgescu et al., 2014). Energy demand by urban residents is predicted to increase over the coming decades. Energy consumption releases waste heat to the ambient environment, thus affecting the intensity and variability of the urban climate. Therefore, having a better understanding of correlations between the environmental effects and energy systems is essential (Theodosiou et al., 2015).

Anthropogenic heat can affect the spatial-temporal variations of urban heat islands. Unlike the landscape transformation which affects urban temperature by altering the sensible and latent heat fluxes, anthropogenic heat represents a direct external source for the urban thermal environment (Menberg et al., 2013; Li et al., 2014; Du et al., 2016; Zhao et al., 2016). Most studies have focused on the effects of land use and population on urban heat islands (Schwarz et al., 2012; Connors et al., 2013) while anthropogenic heat associated with energy consumption in cities has been largely simplified in many studies of urban climates (Sailor, 2011; Du et al., 2016). This is particularly true for studies which focus on the spatial and temporal heterogeneity of urban heat islands (Huang et al., 2016). A recent study showed that, over the last decade in China, the contribution of fossil-fuel CO_2 to urban climates has become more from fossil fuels than from land-use change (Li et al., 2016). Anthropogenic heat in the life cycle of

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energy consumption not only reflects the environmental consequences but also represents the energy utilization efficiency. A study showed that about 250,000 people could die each year because of urban heat waves by 2050 (McDonald et al., 2016). Cities thus should take proactive steps to adapt to urban warming. Recent studies have found that use of renewable energy sources, cleaner fuels and more effective technologies for energy systems is increasing due to the need for mitigating the urban warming. Anthropogenic heat assessment has the potential to be a component of multicriteria analysis for the design and planning of energy systems (Theodosiou et al., 2015).

Anthropogenic heat sources include emissions from human metabolism, industrial processes, buildings, and vehicle combustion (Sailor and Vasireddy, 2006). Because the anthropogenic heat emissions vary spatially and temporally (diurnally, weekly, seasonally, and yearly), research results based on data from localized areas and specific times cannot elucidate the correlation between anthropogenic heat and the variability of urban temperatures. So far, the contribution of anthropogenic heat to urban environments remains poorly understood. For example, anthropogenic heat in some US cities was reported at about 20–40 Wm^{-2} in summer while 70–210 Wm^{-2} in winter (Heiple and Sailor, 2008). The maximum values of anthropogenic heat reached 280–870 Wm^{-2} in Tokyo and even 1590 Wm^{-2} in high density residential and commercial areas of the city (Ichinose et al., 1999). A previous study revealed that the contribution of anthropogenic heat to the sensible heat flux in spring was lower than the contributions in summer and winter (Kato and Yamaguchi, 2005). Therefore, appropriate approaches and models are extremely important when investigating the contribution of anthropogenic heat emissions in different locations and seasons.

Large-scale research has been implemented in the US (Sailor and Vasireddy, 2006; Flanner, 2009), UK (Smith et al., 2009), and Asian cities (Lee et al., 2009) while city-scale studies are available for Tokyo (Ichinose et al., 1999), New York (Howard et al., 2012), London (Iamarino et al., 2012), Indianapolis (Zhou et al., 2012), Phoenix (Chow et al., 2014), and Sydney (Ma et al., 2017), etc. Recent studies have introduced more supplementary parameters to improve the results of anthropogenic heat calculation by the inventory approach (Offerle et al., 2005; Pigeon et al., 2007; Park et al., 2016). The ability of anthropogenic heat models to predict the patterns of temporal and spatial variations, however, is limited and will require further research (Best and Grimmond, 2016; Chrysoulakis and Grimmond, 2016).

We conducted this study to (1) quantify the spatial and temporal variations of anthropogenic heat based on the energy consumption data; (2) assess the contributions of anthropogenic heat to the urban environment in different seasons. To do this, we developed a distributed model of anthropogenic heat (DMA) based on the inventory approach. The DMA quantified the anthropogenic heat intensity by separately considering the major sources of waste heat in urban environments from buildings, human metabolism, industry, and vehicular traffic. The spatial units of DMA were designated as the urban functional zones (UFZs) which were defined not only by their spectral characteristics but also by their social and economic functions in a city. A UFZ type may include several types of land use and have usually been organized by specific urban functional types. Therefore, a UFZ might have similar intensity and structure of energy consumption (Tian et al., 2010; Sun et al., 2013). The use of UFZs can provide more accurate information than use of land use. The DMA combined urban function with energy consumption to provide a feasible method for anthropogenic heat management in different urban regions.

For a case study, the model was implemented based on detailed UFZs in the Beijing metropolis. Beijing is the capital of China and serves as the centers of politics, culture, innovation, and international exchange. It should therefore be an ideal site to examine the anthropogenic heat variations associated with different UFZs. The results of this study could provide implications of selecting prioritized areas and specific season to implement urban mitigation projects.

2. Materials and methods

2.1. Study area

Beijing lies within a warm temperature zone and has a typical continental monsoon climate. After the rapid urbanization in the last three decades, the total population of Beijing exceeded 21.7 million and the total number of automobiles reached 5.5 million by the end of 2016 (BSIN, 2017). Energy consumption in Beijing increased from 19 million tce (ton coal equivalent) in 1980 to 68.5 million tce in 2015 (BSIN, 2017). Anthropogenic heat emissions increased the intensity of the urban heat islands in Beijing (Huang et al., 2016). The mean intensity of urban heat islands between 1998 and 2011 was 0.4 °C higher than that between 1984 and 1997 (Fu and Weng, 2016). The pattern of development in Beijing occurred in a typical concentric expansion, generating a ring-shaped pattern from the city center to the outskirts. We have found a temperature gradient of 0.1 °C/km from city center to outskirts (Sun and Chen, 2017). This study was targeted at the highly-urbanized region inside the 5th ring-road of Beijing, which covered an area of 667 km^2. This region was relatively flat, with elevations ranging from 20 m to 60 m above sea level (a.s.l.). The study area was divided into seven districts, including Chaoyang, Daxing, Dongcheng, Fengtai, Haidian, Shijingshan, and Xicheng districts. These districts were organized by 120 sub-districts which represent the basic administrative units in China.

2.2. Remote sensing and statistical data

The IKONOS satellite has a high-resolution sensor which includes four multispectral bands (3.2 m) and a panchromatic band (0.8 m). Based on images from the IKONOS satellite in 2012, we manually delineated the entire study area into urban blocks along with a delineation of urban roads and canal networks. The urban blocks were grouped into seven UFZ types: agricultural, commercial, campus , industrial, public, preservation, and residential zones (Sun et al., 2013). Detailed spatial and social information for these UFZs was mainly identified using IKNOS images and Google Maps. Each urban block was then geocoded with a specific type of social function (Table 1). Field verification was implemented for each UFZ type. Finally, the study area was divided into 6941 UFZs (Fig. 1).

We used the statistical data of energy consumption and economy from the 2012 Statistical Yearbook Series of Beijing (BSIN, 2017). The energy consumption in seven districts was reallocated into different UFZs based on the distributed model described in the following section. The vehicle energy consumption data were collected in the seven districts. The weight of vehicle density in each UFZ was calculated based on the traffic congestion index from the Beijing Traffic Management Bureau. The GDP data were collected based on the 120 sub-districts. The structure of GDP sections was determined based on the social functions of each of the seven districts. The population density was calculated in each UFZ based on the data of residential communities of Beijing.

2.3. Anthropogenic heat model

Three types of approaches have been used to estimate the anthropogenic heat, including measures of the surface energy