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A multi-method and multi-scale approach for estimating city-wide anthropogenic heat fluxes

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HIGHLIGHTS

- Urban anthropogenic heat (Q_F) was estimated over different spatial-temporal scales.
- We utilised a novel multi-method approach (inventory and BEM) to estimate Q_F.
- Our approach shows improved Q_F sensitivity to weather vs. previous methods.
- Strong regional variations in Q_F exist, especially notable over space and time.

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ABSTRACT

A multi-method approach estimating summer waste heat emissions from anthropogenic activities (Q_F) was applied for a major subtropical city (Phoenix, AZ). These included detailed, quality-controlled inventories of city-wide population density and traffic counts to estimate waste heat emissions from population and vehicular sources respectively, and also included waste heat simulations derived from urban electrical consumption generated by a coupled building energy – regional climate model (WRF-BEM + BEP). These component Q_F data were subsequently summed and mapped through Geographic Information Systems techniques to enable analysis over local (i.e. census-tract) and regional (i.e. metropolitan area) scales. Through this approach, local mean daily Q_F estimates compared reasonably versus (1.) observed daily surface energy balance residuals from an eddy covariance tower sited within a residential area and (2.) estimates from inventory methods employed in a prior study, with improved sensitivity to temperature and precipitation variations. Regional analysis indicates substantial variations in both mean and maximum daily Q_F, which varied with urban land use type. Average regional daily Q_F was ~13 W m^{-2} for the summer period. Temporal analyses also indicated notable differences using this approach with previous estimates of Q_F in Phoenix over different land uses, with much larger peak fluxes averaging ~50 W m^{-2} occurring in commercial or industrial areas during late summer afternoons. The spatio-temporal analysis of Q_F also suggests that it may influence the form and intensity of the Phoenix urban heat island, specifically through additional early evening heat input, and by modifying the urban boundary layer structure through increased turbulence.

1. Introduction

A significant aspect of the growth of cities is the *urban metabolism* function, which is the sum of all materials and commodities produced and/or utilized in order to sustain a city's inhabitants (Wolman, 1965). The generation of waste heat, water and pollutants

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into the atmosphere from the metabolism directly alters near-surface urban climates, especially over different spatial and temporal scales (Oke, 2006). One prominent feature in urban meteorological research is the input of anthropogenic heat and moisture emissions associated with energy consumption from various sources within cities. These can originate through consumption of electricity and heating fuels originating from buildings or industrial activities, combustion of fuel from vehicular traffic, and activities associated with human metabolism; these inputs are hereafter referred to as Q_F (Sailor, 2011).

The influence of Q_F on local-scale urban climates can be considerable. Within mid- or high-latitude cities during winter, waste heat from urban metabolism can be significant in urban heat island (UHI) development (e.g. Magee et al., 1999; Fan and Sailor, 2005). This feature arises due to smaller geographical input of solar radiative fluxes relative to low-latitude cities, as well as comparatively thinner winter urban boundary layers when compared to warmer, more turbulent summer conditions. This impact of Q_F on surface air temperatures may not be restricted to cities and their nearby environs. Given the rapid rate of global urbanization, and corresponding rates of energy consumption, there is a possibility that combined waste heat from multiple large cities could also increase winter nocturnal near-surface temperatures at regional scales e.g. the North American and European continents (Zhang et al., 2013).

Q_F is a component of the urban Surface Energy Balance (SEB), and SEB is quantified by the following equation of flux densities (Oke, 1988):

$$Q^* + Q_F = Q_H + Q_E \pm \Delta Q_S \pm \Delta Q_A \left(\mathrm{Wm^{-2}}\right) \tag{1}$$

where Q^* = net all-wave radiation, Q_H = sensible heat, Q_E = latent heat, ΔQ_S = net heat storage, and ΔQ_A = turbulent heat advection into the urban system.

Existing urban SEB work is primarily focused on observation, e.g. through eddy covariance (EC), or modeling e.g. through numerical or physics-based models of other terms in Equation (1) apart from Q_F (e.g. Grimmond et al., 2010). In contrast, there are three extant approaches to directly estimating Q_F. First, by the inventory of electrical consumption across different urban sectors, such as from buildings, industry and transport. Second, via Q_F based on accurate parameterizations of coupled building energy models that simulate waste heat rejected into the atmosphere of regional or global climate models. Third, through derivation of waste heat from closure of urban SEB using EC flux data residuals. Sailor (2011) reviewed several methodological limitations with respect to each of these methods, such as the lack of data availability over differing spatio-temporal resolutions for the inventory of Q_F arising from buildings, industry and transport; the relative complexity and computational cost of running coupled building energy-regional climate models; and the high cost of installing and logistical difficulties in operating an urban EC tower for estimating the urban SEB, as well as its implicit error uncertainties with respect to EC data residual accuracy. Notably, he suggested that future research should consider utilizing a combination of these approaches in estimating Q_F.

Despite these limitations, research originating from several European (e.g. Christen and Vogt, 2004; Offerle et al., 2005; Pigeon et al., 2007; Allen et al., 2010; Iamarino et al., 2012; Bohnenstengel et al., 2013; Lindberg et al., 2013; Ward et al., 2013), Asian (e.g. Ichinose et al., 1999; Dhakal and Hanaki, 2002; Lee et al., 2009; Quah and Roth, 2012), Australian (Simmonds and Keays, 1997), and North American cities (e.g. Taha, 1997; Sailor and Lu, 2004; Fan and Sailor, 2005; Grossman-Clarke et al., 2005; Salamanca et al., 2013, 2014) enable us to infer several observations about Q_F:

- Spatial variations in urban land-use are important in Q_F with largest mean fluxes originating from areas with commercial or industrial land-uses, which generally have greater energy demand and consumption compared to residential land-uses. The former land-uses are usually concentrated in urban downtown core areas, while the latter corresponds with suburban areas or the urban-rural boundary. Coincidentally, this spatial pattern of Q_F matches the typical distribution of the UHI intensity across a city (Oke, 1982). Further, areas adjacent to major traffic thoroughfares (e.g. highways/freeways) were also associated with relatively higher Q_F compared to areas with local roads due to greater volume of vehicle heat and moisture emissions.
- Temporal variations are also significant in Q_F dynamics. In sub-diurnal or hourly time scales, peak fluxes tend to coincide with both morning and evening rush hour periods, and can be a large component of the urban energy balance relative to other radiative (i.e. incoming short-wave and outgoing long-wave with respect to the urban surface) or turbulent transfer (i.e. sensible and latent heat) terms. On longer time scales (daily, monthly or annual), this may not be the case. Taha (1997) noted that daily mean Q_F flux in city centers (e.g. 20–40 W $\mathrm{m^{-2}}$ in summer) are much smaller compared to mean incident shortwave radiation, which is usually an order of magnitude larger.
- The seasonal impact of Q_F largely depends on a city's geographical location. On average, Q_F fluxes are greater during winter in mid/high-latitude cities, where waste heat from residential heating is greater than those generated from summer air-conditioning in low-latitude cities. For most cities, more energy is consumed through heating, rather than cooling, to maintain a comfortable ambient temperature for human thermoregulation (Hill et al., 2013). For instance, Ichinose et al. (1999) noted in their model simulations in Tokyo (35.6 °N) that a remarkable peak winter hourly Q_F of ~1590 W $\mathrm{m^{-2}}$ occurred in the downtown/commercial area of the city, with most of this waste heat originating from building hot water supplies for indoor heating. In contrast, Quah and Roth (2012) estimated that a maximum hourly Q_F in downtown Singapore (1.4 °N), where building interior cooling via air conditioning is prevalent, was ~113 W $\mathrm{m^{-2}}$.

In the majority of previous research, Q_F estimates were restricted to a single method (i.e. assessing waste heat through inventory, energy balance residual from an EC tower, or through extant building energy models). Although Offerle et al. (2005) and Pigeon et al. (2007) were notable exceptions as they used multiple methods in estimating Q_F for Lodz and Marseille respectively, their analyses were restricted to a single, local spatial scale (<1 $\mathrm{km^2}$). There remains a gap in the extant literature for the application of multiple-method approaches for Q_F analysis as suggested by Sailor (2011). A useful application of this combined approach would enable examination of Q_F across multiple spatial and temporal resolutions, which potentially yields useful results in interpreting these Q_F data. Thus, in this study, we use a variety of methods to map and analyze Q_F for a major city – Metropolitan Phoenix, Arizona – at both local (i.e. for a residential neighborhood around an EC tower) and meso-scales (i.e. for the entire metropolitan area). We attempt to answer the following research questions: (1.) what are the typical summer Q_F profiles across metropolitan Phoenix; (2.) what are the relative contributions of building energy consumption, emissions from vehicular traffic, and human metabolism towards these distributions of Q_F, and; (3.) how do these profiles compare with derived local-scale EC flux residuals from a residential area?