SPATIAL AND TEMPORAL DISTRIBUTION OF ANTHROPOGENIC HEAT EMISSIONS IN SINGAPORE

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Abstract

The anthropogenic heat flux, Q_F, can potentially be a significant contributor to the urban energy balance. In this study, Q_F was estimated by individually considering the major sources of waste heat in urban environments, which are heat released from vehicular traffic, buildings and human metabolism. These components of Q_F were estimated by using a combination of the top-down and bottom-up modelling approaches of energy consumption in the context of Singapore. Using this method, the diurnal and weekly variability of Q_F were determined for three typical land use types found in Singapore, namely, (i) commercial, (ii) high density public housing and (iii) low density private housing.

Key words: anthropogenic heat flux, waste heat, heat emissions, energy consumption, Singapore

1. INTRODUCTION

The anthropogenic heat flux, $Q_{F,}$ is unique to urban environments. It is essentially the energy released from human activities such as vehicle fuel combustion, heating and cooling of buildings, usage of electrical appliances and human metabolism. Very often Q_F is regarded as negligible in urban climate studies due to its modest magnitude relative to the other fluxes of the urban energy balance. However, in densely populated cities with high energy demands, Q_F may play an important role in affecting the urban thermal environment, ambient air quality, and other attributes of the urban climate system. Given that Singapore has a strong demand for air-conditioning throughout the year and is one of the world's most densely populated countries, it is worthwhile to observe and evaluate the magnitude of Q_F for this tropical city state as part of a larger study on the urban climate of Singapore.

Many past anthropogenic heat studies have attempted to quantify Q_F using the inventories of energy consumption method (e.g. Grimmond, 1992; Klysik, 1996; Sailor and Lu, 2004; Pigeon *et al*., 2007). Some of these past studies have introduced certain concepts in relation to this method of estimating Q_F. Specifically, Grimmond (1992) developed the bottom-up modelling approach of energy consumption to obtain the magnitude of Q_F for Vancouver, British Columbia. This approach relies on estimating energy consumption at small-scales (e.g. individual buildings) in order to scale the information up to larger scales of interest (e.g. city-scale). Sailor and Lu (2004) introduced the top-down modelling approach of energy consumption and used it to estimate the Q_F values for several major cities in the US. Contrary to the bottom-up modelling approach, the top-down modelling approach requires data to be obtained at large aggregate scales (e.g. yearly) for the purpose of downscaling it to smaller scales of interest (e.g. hourly).

In view of the different modelling approaches of energy consumption that were developed to quantify Q_F, one of the main objectives of the study was to estimate the magnitude of Q_F in Singapore by adapting the above modelling approaches of energy consumption to the local context.

2. STUDY AREA

Singapore is an island city-state located at the southern tip of the Malay Peninsula. Due to its proximity to the equator (about 130 km north), this densely populated country experiences a typical equatorial wet tropical climate with uniformly high monthly mean temperatures (26.4 ˚C – 28.3 ˚C). The study areas were selected to represent some of the common land use types found in Singapore. One area each was chosen from the commercial (COM), high-density public housing (HDB) and low-density private housing (RES) land uses. Figure 1 shows the location of the study areas. A landmark site for each land use type considered in the study was selected as the centre of the

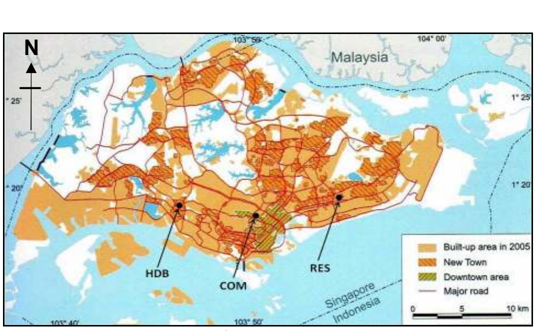

Figure 1: Location of the study areas (black dots). COM, commercial area; HDB, high-density public housing area; RES, low-density private housing area. (Source: de Koninck *et al*., 2008)

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study area. Subsequently, a 500 m radius circle centred on the centre of study area was created to determine the spatial extent of the study area (Figure 2).

3. MODELLING FRAMEWORK TO ESTIMATE Q_F

In the present study, Q_F was estimated as a sum of the major sources of waste heat in urban environments, such that:

$$Q_F = Q_V + Q_B + Q_M \quad [\text{W m}^{-2}] \qquad (1)$$

where Q_V is heat released from the combustion of vehicle fuels, Q_B is heat released from buildings, and Q_M is heat released from human metabolism. The terms on the right-hand side of equation 1 represent the main sources of anthropogenic heat in Singapore. These three terms were calculated using different modelling approaches of energy consumption as summarised in Table 1.

Table 1. Modelling approaches of energy consumption used to calculate the values of the components of Q_F

Component of Q_F	Modelling Approach of Energy Consumption Used
Q_V	Bottom-up
Q_B	Hybrid of top-down and bottom-up
Q_M	Top-down

Past anthropogenic heating studies have assumed that all the energy consumed by vehicles and in buildings is rejected as sensible waste heat into the atmosphere (e.g. Grimmond, 1992; Inchinose *et al*., 1999; Sailor and Lu, 2004). Thus, this assumption was also made for the present study.

3.1. Heat from vehicular traffic

Adapting the approach used by Grimmond (1992), Q_V was computed using the equation:

$$Q_V(h) = [\sum (n_{vijk}(h) \times EV_{ij} \times l_k) / 3600] / A \quad [\text{W m}^{-2}] \qquad (2)$$

with

$$EV_{ij} = (NHC_j \times \rho_j) / FE_{ij}, \quad [\text{J m}^{-1}] \qquad (3)$$

where h is time (hour), subscripts i, j *and* k indicate vehicle type, fuel type and road section respectively, $n_{vijk}(h)$ is the total hourly number of vehicles type i consuming fuel type j and travelling on road section k, l_k is the length of road section k (m), EV_{ij} is the energy used per vehicle type i consuming fuel type j (J m^{-1}), A is the extent of the observation area (m^2), NHC_j is the net heat combustion of fuel type j (J kg^{-1}), ρ_j is the density of fuel type j (kg l^{-1}) and FE_{ij} is the mean fuel economy of vehicle type i consuming fuel type j (m l^{-1}).

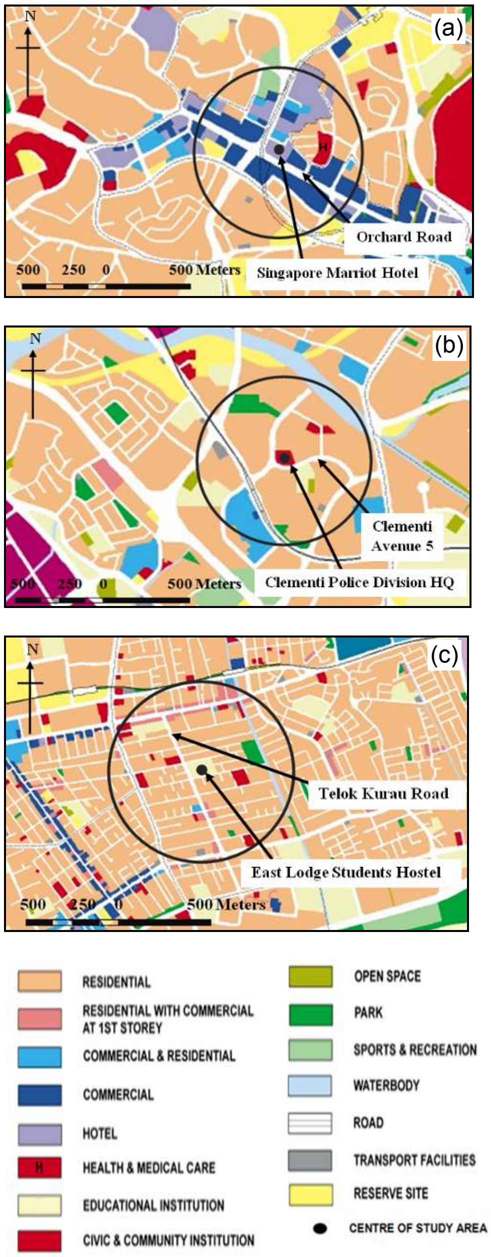

Figure 2: Spatial extent of (a) COM, (b) HDB and (c) RES. (Source: Urban Redevelopment Authority, 2008)

One continuous week's worth of hourly traffic count data for the road segments of interest was obtained from the Land Transport Authority (LTA) of Singapore. This data was considered to be representative of the hourly traffic count data for all weeks of the year as the study assumed that the volume of traffic on Singapore roads shows little weekly and monthly variability.

Different vehicle classes have differing levels of energy usage. As such, a value representative of the energy used by each vehicle class was determined for the study. Factors influencing the amount of energy used by vehicles include the type of fuel used and the vehicle's fuel economy. In Singapore, 99.4% of all vehicles use either unleaded petrol or diesel (Land Transport Authority, 2008). Hence, only these two fuel types were considered. The fuel economy values representative of each vehicle class considered in the study ranged from 2179 m l^{-1} (motorcycles) to 29411 m l^{-1} (heavy vehicles) (LTA, personal communication, 2009).

All road segments found within COM, HDB and RES were digitised in vector form. Using the Measure tool in ArcGis, the length of each road segment of interest was obtained.

3.2. Heat from buildings

The energy consumed within buildings is typically used for purposes of heating, cooling, ventilation and operating appliances. This energy will ultimately be converted into waste heat and released into the atmosphere. Electricity and gas are the only fuel types consumed by the commercial and residential sectors in Singapore. Since gas consumption accounts for just 2.6% of the total energy consumption in the commercial and residential sectors and given the difficulties in obtaining gas consumption data at the required spatial resolution (individual users) and temporal resolution (hourly), only electricity contributions to Q_B were considered in this study (International Energy Agency, 2006). Hence, the approach used by Grimmond (1992) was modified and Q_B was estimated as:

$$Q_B(h) = \sum E_k(h) / A \qquad [\mathrm{W\ m^{-2}}] \qquad (4)$$

where h is time (hour), subscript k indicates building number, $E_k(h)$ is the mean hourly electricity consumption of building k (J hour^{-1}) and A is the observation area (m^2).

Hourly and monthly electricity consumption of the individual buildings of interest had to be estimated as the actual data could not be obtained. The yearly amount of electricity consumed by commercial buildings was estimated from their typical energy efficiency values (measured in kWh/m^2/year) obtained from the Building and Construction Authority of Singapore. The yearly electricity consumption data was then mapped onto monthly, weekly, daily and eventually hourly load profiles, obtained from the energy audit reports of commercial buildings. In terms of residential buildings, the typical monthly electricity consumption of different household types (e.g. 3-room public flat, 4-room public flat, private flats, and private houses) was obtained from SP Services, which oversees the electricity billing service in Singapore. Similar to the commercial buildings, the estimated monthly electricity consumption of households was mapped onto the representative weekly, daily and hourly load profiles for households, obtained from the Energy Market Authority of Singapore. Typical hourly electricity consumption values for the common areas of public and private residential buildings were estimated and then added to the estimated hourly electricity consumption of all households in the building to derive the estimated total hourly electricity consumption of the residential building.

3.3 Heat from human metabolism

Human metabolic rates are not constant throughout the day since individuals engage in various forms of activities at different times of the day. Hence, for the study, the day was divided into two time periods, namely 'active' (07:00 h – 23:00 h) and 'sleep' (23:01 h – 06:59 h). This approach is similar to the one used by Grimmond (1992) to estimate Q_M values in Vancouver, Canada. Eventually, Q_M was estimated from the following equation:

$$Q_M(h) = \sum [n_p(h) \times M_p] / A \qquad [\mathrm{W\ m^{-2}}] \qquad (5)$$

where h is time (hour), subscript p represents the time period ('active' or 'sleep'), n_p refers to the total number of people within the observation area during time period p, M_p is the metabolic rate representative of time period p (W), and A is the observation area (m^2). Using data from Fanger (1972), representative metabolic rates for the active' and 'sleep' periods were estimated to be 305 W and 168 W respectively.

4 RESULTS AND DISCUSSION

Only final results for Q_V and preliminary results for Q_B have been obtained up to now as the study is still on-going. The preliminary results for Q_B exclude contributions of waste heat from civic and community institutions (e.g. police station and welfare homes), and commercial shops located on the first floor of residential buildings and shophouses. These building types were only found in HBD and RES.

Figure 3 shows that the maximum mean hourly Q_V of 15 W m^{-2} was recorded at COM at 19:00 h. The maximum total daily Q_V of 71378 J m^{-2} was also found at COM (Figure 4). These results are not surprising since COM represents the main shopping area of Singapore and has a very high volume of vehicles passing through it on an hourly and daily basis. Figure 3 also shows that for COM, HDB and RES, the mean hourly Q_V values begin to fall after 19:00 h, but remain quite large for a few hours. Q_V only starts to increase from 06:00 h onwards. During the period between 09:00 h and 19:00 h, the mean hourly Q_V values for COM remain fairly stable. Twin peaks in the hourly Q_V profiles of HDB and RES were observed, with one at 08:00 h and the other at 19:00 h. These peak hours correspond to the rush hours when most people leave for work and return home from work. It can be seen from Figure 4 that Q_V values for COM, HDB and RES show little variability throughout the week. The average percentage difference between the mean daily weekday and weekend Q_V values range from about 3% in RES to about 9% in COM.

Figure 5 shows that the maximum mean hourly Q_B (103 W m^{-2}) was found in COM at 11:00 h. After 17:00 h, the mean hourly Q_B values for COM start to drop before stabilising from 24:00 h – 06:00 h. These values begin to increase from 07:00 h onwards as office workers, shoppers and other temporary inhabitants arrive in the city centre. There is a slight dip in the mean hourly Q_B values for COM at 12:00 h. This is perhaps due to offices consuming less energy during lunch time. After the lunch period, the mean hourly Q_B values start to increase again, till 17:00 h. Figure 5 indicates that the mean hourly Q_B values in HDB and RES are likely to be highest from 19:00 h – 06:00 h relative to the rest of the day. Typically during this period, most people are at home and energy consuming appliances such as, air-conditioners, televisions and computers are in use; hence, resulting in higher levels of energy consumption during these hours. It was observed from Figure 6 that the total daily Q_B values for COM, HDB and RES show slight variability throughout the week. At COM, the mean weekday Q_B magnitude was about 10% higher than the weekend value.

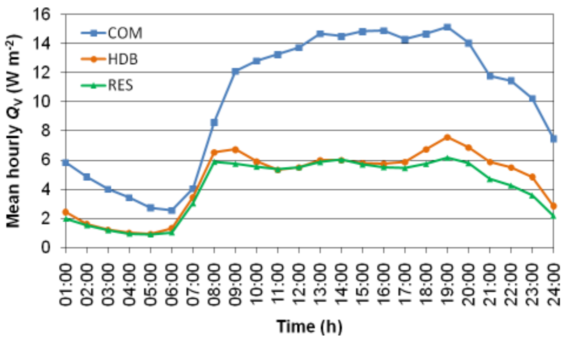

Figure 3: Mean hourly Q_V for COM, HDB and RES

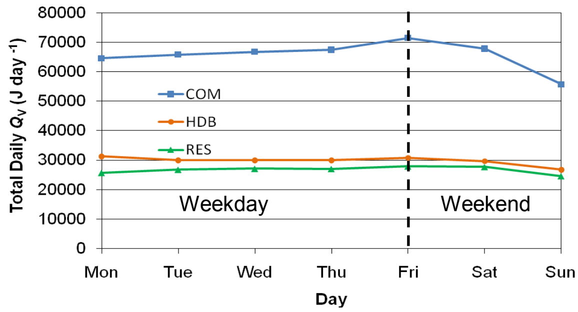

Figure 4: Total daily Q_V for COM, HDB and RES

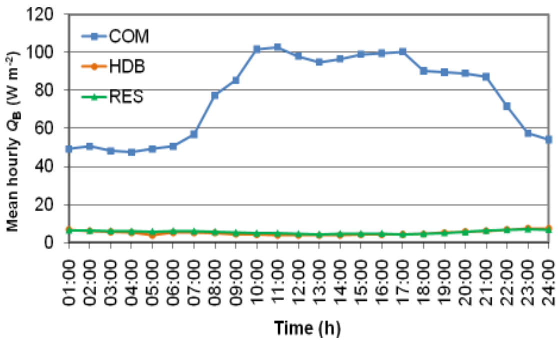

Figure 5: Mean hourly Q_B for COM, HDB and RES

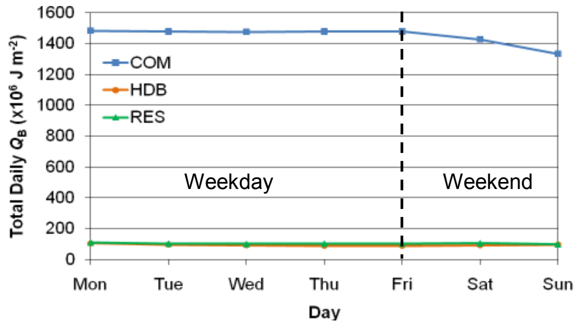

Figure 6: Total daily Q_B for COM, HDB and RES

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