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ORIGINAL PAPER

Estimating spatial and temporal patterns of urban anthropogenic heat fluxes for UK cities: the case of Manchester

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Abstract A model is proposed for determining the temporal and spatial patterns of anthropogenic heat fluxes in UK urban areas. It considers buildings, traffic, and metabolic heat flux sources and has been evaluated to a good accuracy against alternative data for the Greater Manchester area in the UK. Results are presented at spatial resolution of 200 × 200 m although the model itself is scalable depending on data availability. In this paper, results are generated using a set of urban morphology units so that detailed and time-consuming accounting of individual building and road emissions is not required. The model estimates a mean heat emission of 6.12 Wm^{-2} across Greater Manchester, with values in the region of 10 Wm^{-2} for non central urbanized areas and 23 Wm^{-2} in city center areas. Despite this difference, the results are not described by a simple distance decay function, as has been reported for other cities, due to the influence of satellite towns and the influence of the road network. Buildings are the dominant emitter, contributing some 60% of total emissions across the city compared to around 32% for road traffic and 8% for metabolic sources.

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1 Introduction

Traditionally, urban heat island research has focused primarily on the urban-rural contrast in albedo, heat capacity, moisture, and surface roughness. However, there is a growing body of research concerned with the impact of anthropogenic thermal pollution upon the dynamics of the urban boundary layer. While the amount of energy released as a result of anthropogenic activities is a tiny fraction of the energy from the sun intercepted by the earth on a global scale, it is recognized that human energy production density can be substantially higher in urban regions, thus contributing significantly to the local heat island phenomenon (Crutzen 2004). Indeed, by employing a detailed energy consumption inventory approach, several studies have shown a non-negligible contribution from anthropogenic heating to the urban environment. The effect is particularly pronounced during winter, with maximum, localized estimates ranging from 100 Wm^{-2} in central London (Harrison et al. 1984) up to 1,590 Wm^{-2} in central Tokyo (Ichinose et al. 1999). More recent estimates from London energy consumption data suggest annual heat emissions for the central City of London borough have risen to 135 Wm^{-2} (GLA 2007).

The impact of energy consumed as a result of anthropogenic activities is estimated to lead to a 1–3°C augmentation of the heat island effect (Fan and Sailor 2005). Data from aggregate energy consumption statistics suggest a mean annual anthropogenic heat flux of 20 to 160 Wm^{-2} when spatially averaged across large cities. Estimates for US cities range between 20 and 40 Wm^{-2} in summer and between 70 and 210 Wm^{-2} in winter (Taha 1997). This seasonal disparity may, however, become less pronounced for the UK and other Northern European areas under future climate projections, as summer cooling loads become

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greater, and winter heating demand reduces (Hulme et al. 2002; Levermore et al. 2004; Parkinson et al. 2004). For example, the sensitivity of electricity demand (due to air-conditioning of buildings) to urban warming in US cities is predicted to be 3-6% for every 1°C temperature increase (Bretz et al. 1998) and, similarly, 6.6% for every degree of warming in Tokyo (Kondo and Kikegawa 2003).

The inflated city center values of the anthropogenic heat flux, estimated to be an order of magnitude higher than spatially averaged values (Sailor and Lu 2004), suggest that waste heat could be responsible for localized variations in the urban thermal environment. This has particular implications with regard to the risk to the urban population from summer overheating and, conversely, the opportunity for alleviating the risk of winter cold through fuel-poverty induced vulnerability. Therefore, producing fine-scale spatially and temporally resolved anthropogenic heating profiles would be of value not only for inclusion to, and the evaluation of, urban energy balance models (e.g., Dhakal and Hanaki 2002), but also for use by urban planners and designers to understand and better manage the future impacts of a changing climate on patterns of risk within urban populations (Lindley et al. 2007).

However, in contrast to the fine-scale temporal and spatial modeling of the anthropogenic heating effect that has been undertaken for Japanese (Ichinose et al. 1999; Dhakal and Hanaki 2002) and North American cities (Grimmond 1992; Sailor and Lu 2004; Heiple and Sailor 2008), there has been limited effort to produce similarly detailed anthropogenic profiles for UK cities since the estimates were produced by Harrison et al. (1984) for London during the early 1970s. This is in spite of the wide array of publicly accessible UK energy consumption (DTI 2002) and socio-economic datasets (Census 2001), which are available at sub-regional spatial scales. Furthermore, recent changes to legislation now demand that the energy performance of a building is accurately monitored using automatic metering, and that this information is made accessible via Display Energy Certificates (Building Regulations: Part L 2006; EPBD 2007). All of which can assist in the spatial and temporal disaggregation of the anthropogenic heating profile within UK cities.

The current work aims to develop and apply a generic modeling framework for the calculation of the anthropogenic heat flux that can be applied to cities within the UK and elsewhere. The approach taken will essentially be a bottom-up approach that uses readily available data and provides output at 200 ×200 m grid square resolution. All estimates shall be verified using aggregate energy statistics from the UK Department for Business, Enterprise and Regulatory Reform (BERR; formerly the Department for Trade and Industry). The output dataset will then feed into ongoing research into the urban heat island effect as part of the UK EPSRC-funded SCORCHIO (Sustainable Cities: Options for Responding to climate CHange Impacts and Outcomes) project, which will examine future changes to the anthropogenic heat flux under different local development scenarios.

The following section outlines the model framework which is used to calculate heat emissions. The results of applying the model to a case study UK city are given in Sect. 3 and these are discussed in more detail in Sect. 4.

1.1 Modeling framework

The major sources of waste heat, Q_F, in the urban environment can be divided into three components:

$$Q_F = Q_{FV} + Q_{FB} + Q_{FM} \left(Wm^{-2}\right) \quad (1)$$

Here, the subscripts V, B and M represent vehicular, building and human metabolic heat emissions, respectively. Metabolic heat is often assumed negligible relative to vehicle and building heat production but shall be incorporated into the model for completeness. As in previous studies (Ichinose et al. 1999; Kondo and Kikegawa, 2003; Betts and Best 2004), the model assumes anthropogenic heat is equivalent to energy consumption and that there is no time delay between the consumption of energy and the emission of the exhaust heat, which will have implications for the diurnal anthropogenic heating profile (Dhakal and Hanaki 2002; Heiple and Sailor 2008). For the building heat emissions, the time delay between consumption and emission is a function of building type, fabric and the HVAC (Heating, Ventilating and Air-Conditioning) system used and cannot be fully captured by the categorization of buildings by land use implemented here (see Sect. 2.3). Therefore, the assumption of no time delay is necessary in the current study. A more detailed investigation of the specific relationship between energy consumption and heat emission will be the subject of future work.

Building heat emissions are derived using information about land use. This is a novel approach that offers a good compromise between a data-intensive bottom-up method and a less detailed top-down approach. Information about land use is used to determine the type of buildings within an area, and subsequently, the energy use and heat emissions associated with those building types. Total heat emissions are calculated for 200 ×200 m grid squares. This spatial scale corresponds to the smallest spatial scale for which population data have been disaggregated (Martin et al. 1999). It also offers a trade-off between a data-intensive, very fine-scale mesh (tens of meters; e.g., Ichinose et al. 1999) and a coarser kilometer-scale resolution (e.g., Harrison et al. 1984). However, the model is scalable depending on the resolution of the input data.

1.2 Study area

The modeling framework is developed using Greater Manchester as a template but will later be applied to a second case study city in northern England (Sheffield). Greater Manchester is situated in northwest England and covers an area of 1,276 km^2 (Fig. 1). It consists of ten local authorities (LAs): Bolton, Bury, Oldham, Manchester, Rochdale, Salford, Stockport, Tameside, Trafford, and Wigan. The total population is approximately 2.5 million, with population densities ranging from 1,306 people km^{-2} in Rochdale to 3,779 people km^{-2} in Manchester (Office for National Statistics 2008). Total annual energy consumption from the industrial, commercial, domestic and transport sectors for the region in 2004 was 66 141.9 GWh (BERR 2004).

A case study of Greater Manchester is a favorable starting point for the quantification of anthropogenic heat emissions as the region has the benefit of having been characterized, as part of an earlier study, according to 29 urban morphology types (Gill et al. 2007). There is an estimated 23% built surface across the Greater Manchester conurbation as a whole (Gill et al. 2008), rising to 37% for the urbanized area (i.e., excluding farmland areas). In addition, there are over 7,300 km of roads across the conurbation, including major sections of the motorway network, the M60, M6, M62, and M56, which in 2006 had Annual Average Daily Traffic (AADT) flows exceeding 65,000, and in some cases 100,000, vehicles per day (DfT 2007).

Fig. 1 Location of Greater Manchester and its local authority boundaries

2 Methodology

2.1 Vehicular heat emissions

In past research, the quantification of heat emissions from traffic has generally been achieved using a relatively simplistic approach due to the lack of detailed information regarding the variation of traffic density with time, and the variation of heat discharge with vehicle type. For example, Klysik (1996) used sales of petrol and diesel as a proxy for road traffic energy consumption by simply multiplying annual sales for the county by the proportion of the population living in urban areas. Ichinose et al. (1999) divided annual energy use statistics by season and hour and then assumed traffic density was spatially uniform across Tokyo. This method was later refined to examine the hourly spatial variation of traffic heat emissions through the use of a top-down method to disaggregate data, for example by multiplying the heat discharge per unit of road area obtained from Ichinose et al. (1999), by the total area of roads in a 250 ×250 m grid square (Dhakal and Hanaki 2002).

Here, the approach taken is a bottom-up method more in line with that of Grimmond (1992) who used traffic count data, n_i, where i is the road type (major/minor), from the local traffic department, to estimate Q_{FV}:

$$Q_{FV} = \frac{[(n_i(t)L_i)EV]}{A \times 3600}\,(W\mathrm{m}^{-2}) \tag{2}$$

The remaining input parameters are the time of the day, t (hours), the length of the road, L_i (m), a consumption factor, EV (Jm^{-1}), and the source area, A (m^2). However, the approach taken here benefits from a more detailed spatial representation of traffic count data relative to that used by Grimmond (1992).

Road traffic flows for Greater Manchester have been estimated in previous work (Lindley et al. 2006). The network of motorways, A (major)-, B (classified minor) - and unclassified minor roads across Greater Manchester was established using 1:50000 scale UK Ordnance Survey Meridian 2 data. AADT count data obtained from the Department for Transport (DfT; http://www.dft.gov.uk/matrix/) were subsequently used to assign traffic flows for vehicle classes of two-wheeled motor vehicles, cars, buses and coaches, Light Goods Vehicles (LGVs), 2-, 3- and 4+ axle rigid Heavy Goods Vehicles (HGVs) and 3-, 4- or 6+ axle articulated HGVs, to individual roads. Available data also includes other information useful for the calculation of heat emissions, including speed limit and carriageway width.

In the present study, the traffic component of Q_{FV} is calculated using:

$$Q_{FV} = \frac{\sum (n_{mri}(t)L_{ri})EF_{mr}}{A_i}\,(W\mathrm{m}^{-2}) \tag{3}$$

where n_{mri} is equal to the number of vehicles of type m on road r in grid square i, t is the hour of the day, L_{ri} is the length of road r in grid square i, EF_{mr} is a speed-dependent fuel consumption emission factor, which is available from the UK Transport Research Laboratory (Barlow et al. 2001) and A_i is the source area (generally A_i=200×200 m= 40,000 m^2). The model enables equivalent figures to be provided assuming the source area for the traffic emissions is restricted to the road area. The parameters and the method for calculating each of them are described in Table 1.

Traffic flow data for minor roads were not available at such high resolution as they are for the major roads. These roads are instead assumed to have a uniform daily flow, taken as the average traffic flow on 'built-up' minor roads in the northwest, of 1,700 vehicles per day (DfT 2001). Although it could be argued that an AADT of 1,700 is a considerable over-estimate of flows on the majority of minor roads within the city, this is taken as representative for the city as a whole, i.e., including contributions from highly trafficked minor roads in and around the city and satellite town centers.

The heat emissions function (EF) for the range of fleet types is available using speed-dependent fuel consumption factors from the Transport Research Laboratory (TRL; Barlow et al. 2001). In order to use the AADT data to calculate fuel consumption using the TRL emissions database, it is necessary to further disaggregate the vehicular fleet by engine size (for cars only), fuel type (diesel and petrol; for cars and LGVs only) and emissions standard. The regulatory emissions standard (e.g., pre-Euro 1, Euro 1, Euro 2, etc.) describes the standard a vehicle or engine had to comply with when manufactured or first registered (Barlow et al. 2001). Although not directly related to fuel consumption, the standards are indirectly representative of fuel use as they are derived as a function of age, and therefore reflect the associated improvements in fuel economy over time (Goodwin et al. 2005). Information about emissions standards, together with fuel type, is estimated using fleet composition data from the National Atmospheric Emissions Inventory (NAEI 2003; Table 2). NAEI data for the year 2003 were used to correspond with the AADT data. Two issues arise from the use of these data:

1. The fleet composition data from the NAEI are given in terms of fraction of vehicle kilometers traveled, not just vehicle stock, and may therefore give a biased impression of the local fleet composition.
2. The NAEI data include proportions of vehicles with emissions standards of Euro 3 and 4, for which there is no method of calculating the emissions function. These vehicles are assumed to have emissions factors of Euro 2 vehicles and therefore the emissions will be slightly over-estimated.

Table 1 Table of parameters required to calculate heat emissions from traffic

Parameter	Notation	Unit	Source of data
Grid square number	i	-	Grid square IDs within a 200-m vector grid
Road number (e.g., M60)	r	-	Road number from OS Meridian 2 data
Vehicle type	m	Two-wheeled motor vehicles Car Bus LGV HGV	Estimated from AADT count data from the Department for Transport
Petrol/diesel split for cars and LGVs only	p_{CarLGV}	Ratio	Estimated from NAEI (2003) (see Table 2)
Annual average daily traffic flow	$AADT$	Count	Estimated from AADT count data from the Department for Transport, disaggregated by vehicle type m
Time of day	t	Hour	Diurnal traffic flow profile from Greater Manchester Transport Unit (Ellis et al. 2006)
Length of road contained in grid square i	L_i	m	Calculated through overlay analysis
Vehicle kilometers (vkm) per vehicle group and gridsquare	n_{mi}	km	$L_i \times AADT_m$
Emissions function per vehicle group and road type	EF_{mr}	g/km	National Atmospheric Emissions Inventory $EF=(a + b.s + c.s^2 + d.s^e + f.\ln(s) + g.s^3 + h/s + i/sv^2 + j/s^3)$ (Barlow et al. 2001)
Speed on different road classes	s_r	kph	Function of road type and location Motorway -112.6/96.5 kph (70/60 mph) A Road – 64 kph (40 mph) B Road – 48 kph (30 mph)
Source area	A_i	m^2	Calculated area of grid square

Table 2 Fleet composition by emissions standard (NAEI 2003)

	Vehicle standard	% of fleet (2003)
Petrol cars (85.31% of all cars)	Pre Euro 1	15
	Euro 1	19
	Euro 2	66
Diesel cars (14.69% of all cars)	Pre Euro 1	5
	Euro 1	24
	Euro 2	71
Petrol LGV (14% of all LGVs)	Pre Euro 1	28
	Euro 1	14
	Euro 2	58
Diesel LGV (86% of all LGVs)	Pre Euro 1	9
	Euro 1	17
	Euro 2	74
Rigid HGV (HGVR)	Pre-1988	1
	1988-1993	6
	Euro 1	16
	Euro 2	77
Artic HGV (HGVA)	1988-1993	2
	Euro 1	10
	Euro 2	88
Bus/coach	Pre-1988	8
	1988-1993	8
	Euro 1	14
	Euro 2	70

However, the variation in the emissions factor (EF) is generally small enough within vehicle categories (two-wheel motor vehicle, cars, LGVs., etc.) for different engine sizes and emissions standards to have a limited effect on the resultant heat emissions. For example, the EF for petrol cars with emissions standards ECE15.03, ECE15.04, Euro 1 and Euro 2 traveling at 113 kph (70 mph) are 62.26, 56.81, 58.87, and 57.37 g km^{-1}, respectively. The corresponding heat emissions are 36, 33, 34, and 33 Wm^{-2}. Therefore, the error incurred under the assumptions associated with using the NAEI data is considered small enough to be suitably representative of the heat emissions.

The proportional split of vehicular engine sizes are also taken from the NAEI fleet composition data. These are 47.3%, 46%, and 6.7% for petrol cars with engine size less than 1.4l, 1.4-2l and greater than 2l, respectively. Diesel cars are split 84.3% with engine size less than 2l and 15.7% with greater than 2l engines. Finally, an estimate of speed is required to calculate the fuel consumptions and this is assumed to be 113 kph (70 mph) for motorcycles, cars and LGVs and 97 kph (60 mph) for HGVs, coaches and buses on motorways, 64 kph (40 mph) for all vehicles on A roads and 48 kph (30 mph) for all vehicles on B- and minor roads. These speeds are estimated from information contained in the Transport Statistics Bulletin (DfT 2003).

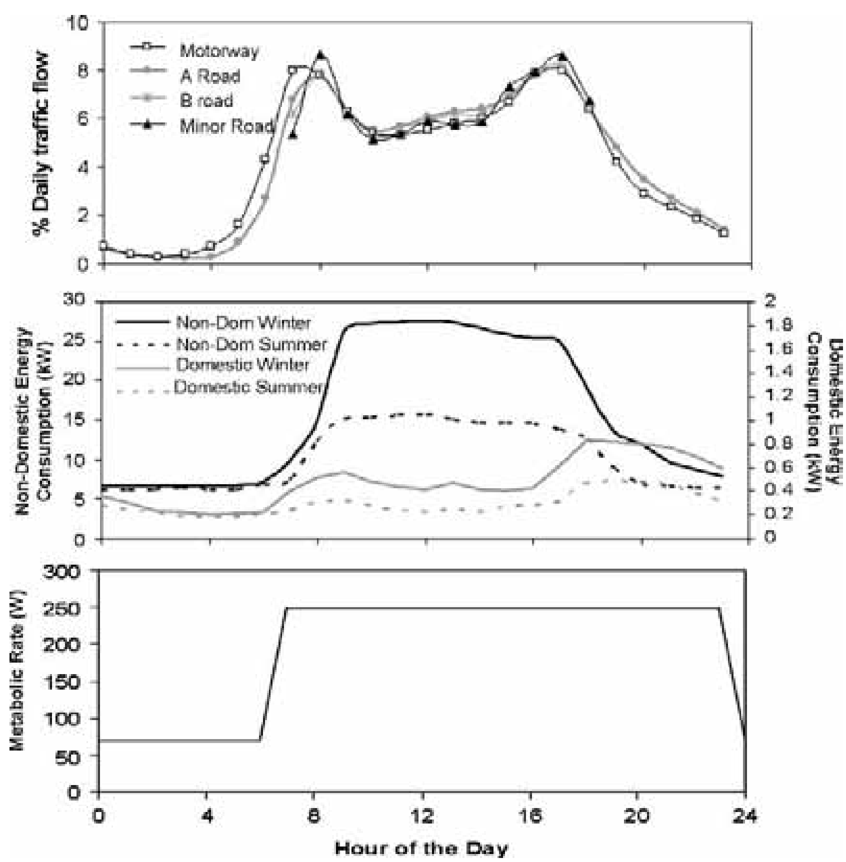


Fig. 2 Diurnal profiles for **a** traffic flow (Ellis et al. 2006), **b** domestic and non-domestic building energy consumption, **c** human metabolic rate

The sensitivity of the estimated heat emissions to these speeds is examined later.

Together this information can be used to calculate the fuel consumption EF (g km^{-1}) for each vehicle category across the range of road types, minor roads up to motorways, in Greater Manchester. The fuel consumptions are then converted to heat emissions by assuming heat combustions of 45.85 kJ g^{-1} (the average of 44.8 and 46.9 kJ g^{-1}) for petrol and 46 kJ g^{-1} for diesel (National Physical Laboratory 2008). Estimates of the calorific values of petrol and diesel do vary, however, with heat combustion values for petrol ranging from 43 to 48 kJ g^{-1} and for diesel ranging from 44.8 to 46 kJ g^{-1} (Hillier and Pittuck 1991). Therefore the sensitivity of the vehicle component of the anthropogenic heat flux to these values is also investigated below.

In order to capture the temporal fluctuations in traffic heat emissions, the daily traffic flows are multiplied by a weighting factor related to the time of day t (Ellis et al. 2006). The diurnal variation of traffic flow in Greater Manchester is very similar across the various road types (Fig. 2a). These diurnal profiles were averaged to give hourly weighting factors for all roads in Greater Manchester.

2.2 Building heat emissions

Due to the difficulties in apportioning aggregate energy consumption statistics to a fine spatial resolution (Harrison et al. 1984), the approach taken here is to calculate the heat emissions from buildings using the urban characterization of Greater Manchester, developed as part of the ASCCUE (Adaptation Strategies for Climate Change in the Urban Environment; http://www.k4cc.org/bkcc/asccue) project (Gill et al. 2008). This is a novel method, which allows buildings to be categorized rapidly according to the land use zone in which they are situated. This bottom-up methodology is in accordance with the calculation of the traffic heat emissions and will be verified using the Greater Manchester BERR (2004) energy consumption data, which is available at local authority level.

Greater Manchester land use was categorized by Gill et al. (2007) into 29 Urban Morphology Types (UMTs) compatible with the National Land Use Database (Table 3). To quantify the surface cover properties of each UMT, the proportional cover of nine different land surface types (building, other impervious, tree, shrub, mown grass, rough grass, cultivated, water, and bare soil/gravel) has been estimated using 400 random sample points within each UMT class (*ibid.*). Therefore, to calculate the built surface cover for each grid square, the grid squares are reclassified according to the areas of the UMTs found within them. Since the proportional built surface cover has been estimated for each UMT (Blt_{UMT}; Table 3) using the random sampling method, it is possible to sum the areas of built surface for each UMT within a particular grid square to calculate the total built footprint area for each grid square.

In addition to the building footprint areas, the energy consumptions of the building types associated with each UMT, EC_{UMT}, are also required to calculate heat emissions:

$$Q_{FBi}(t) = \frac{\sum (A_{UMT} Blt_{UMT} EC_{UMT})}{A_i} \quad (4)$$

where A_{UMT} is the area covered by each UMT within grid square i. Typical building energy consumptions (Table 3) are inferred for each UMT using information from a variety of sources. The CIBSE Guide F 'Energy Efficiency in Buildings' (CIBSE 2004) provides energy consumption benchmarks for several non-domestic building types and

Table 3 Table showing the proportion of built surface for each UMT from Gill (2006) and the typical energy consumption for a building in each UMT category, estimated from values given in CIBSE Guide F (CIBSE 2004) and Elsayad et al. (2002)

UMT category	Proportional built surface cover (Blt_{UMT})	Typical energy consumption (Wm^{-2}) (EC_{UMT})
Improved farmland	0.010	20
Unimproved farmland	0.000	N/A
Woodland	0.003	30.67
Mineral workings and quarries	0.010	50
Formal recreation	0.007	20
Formal open space	0.023	35
Informal open space	0.008	20
Allotments	0.030	15
Major roads	0.025	45
Airports	0.052	45
Rail	0.012	40
Rivers and canals	0.000	0
Energy production and distribution	0.122	50
Water storage and treatment	0.050	50
Refuse disposal	0.002	50
Church yards	0.005	15
High-density residential	0.305	30.67
Medium-density residential	0.217	30.67
Low-density residential	0.142	30.67
Schools	0.080	20
Hospitals	0.272	60
Retail	0.227	80
Town center	0.260	70
Manufacturing	0.300	40
Offices	0.172	50
Storage and distribution	0.282	18.7
Disused and derelict land	0.020	0
Remnant countryside	0.010	30

these are complemented by consumption data contained within the 2002 Catalogue – Energy use in the UK non-domestic building stock (Elsayed et al. 2002). Average domestic energy consumption per household is provided by the UK Building Research Establishment (BRE) (available from: http://www.statistics.gov.uk/STATBASE/Expodata/Spreadsheets/D7287.xls).

The consumptions are rounded to a mid-range value, for example school energy consumptions ranged from 16.64 Wm^{-2} for a low consumption primary/middle school to 23.26 Wm^{-2} for a high consumption secondary school, therefore the 'typical' consumption was taken to be 20 Wm^{-2}. Residential buildings were an exception to this process because only one energy consumption value (30.67 Wm^{-2}) was calculated. For UMTs where no benchmark consumption was provided, which tended to be UMTs with a low proportion of building surface cover (<5%; Improved Farmland, Woodland, Formal Recreation, Formal Open Space, Informal Open Space), assumptions about the building types found within these UMTs were used. For example, buildings found within the improved farmland category were assumed to comprise residential buildings, barns or sheds.

At present the method assumes a single typical daily energy consumption for each Urban Morphology Type, in reality, however, there is likely to be significant variation between buildings found within the same UMT polygon, depending upon the size, age and heating, ventilating and air conditioning system characteristics of a building. Sensitivity to the representative energy consumption values is examined later. However, Heiple and Sailor (2008), found building density to be a more critical factor in governing the magnitude of the heat flux than the mixture of building types. Since the proportional built surface cover has been captured as part of the urban characterization of the conurbation it is likely that the sensitivity of the heat emissions to changing energy consumptions will be low.

The diurnal variation of building heat emissions, which is required for mapping the evolution of the anthropogenic heat flux over time, is dependent upon whether a building is domestic or non-domestic and the time of year (e.g., Fig. 2b). The daily building heat flux calculated using Eq. (4) is weighted by the time of the day and season, according to the urban morphology unit a building is found within, to examine the temporal pattern of heat emissions from buildings (Sect. 4). However, no time delay between energy consumption and heat emission is considered here, which implies that estimates of evening emissions presented here are likely to be lower than actual building heat emissions (Heiple and Sailor 2008).

2.3 Metabolic heat emissions

The heat flux from human metabolism is calculated using population data provided through Surpop v2.0 (Martin et al. 1999). Surpop data redistributes UK Census population counts (Census 1991), which are bounded by unfixed, heterogeneously shaped administrative zones, to 200-m gridded estimates of population (Fig. 3), by using a distance decay function applied to the population counts for each zones residential centroid (Bracken and Martin 1989). One issue with these data is that they are rather outdated and the more recent Census data (Census 2001) indicate that there has been a large influx of people into the city since this time. Furthermore, these data relate to an individuals place of residence, and therefore are unable to capture the movements of the population throughout the day. This problem could potentially be overcome through the use of Census interaction

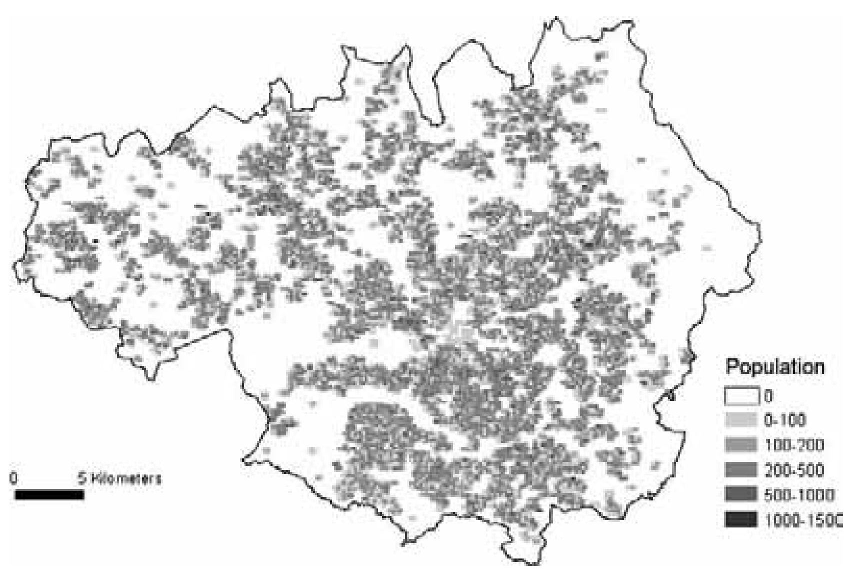


Fig. 3 Population distribution for Greater Manchester at 200× 200 m grid square resolution derived from 1991 UK Census data, after Martin et al. (1999)

data (http://census.ac.uk/guides/Interaction.aspx). However, due to the large volume of data required and the necessary processing of these data, together with the relatively small contribution of the metabolic heat flux, this method is not pursued here.

Given the population distribution across Greater Manchester, the heat flux is calculated by multiplying the population for each grid square, POP_i by the human metabolic rate, Q_M:

$$Q_{FMi}(t) = [POP_i Q_M(t)]/\mathrm{A_i}$$

The metabolic rate fluctuates over the course of a day in response to activity level. Oke (1987) gives human metabolic rates for different levels of activity. These range from 70 W while sleeping to over 800 W for vigorous activity. Figure 2c displays a representative metabolic diurnal profile which is used to calculate the metabolic heat emissions.

3 Results

3.1 Heat emissions from traffic

The calculated traffic heat emissions estimated for roads across Greater Manchester range from 0 $\mathrm{Wm^{-2}}$ (no road) to over 70 $\mathrm{Wm^{-2}}$ at major junctions on the M60 (Fig. 4). However, by limiting the heat flux to the source area, which is the small proportion of each grid square that is attributed to road surface, traffic heat emissions are much higher, approaching 500 $\mathrm{Wm^{-2}}$ at major junctions and over 100 $\mathrm{Wm^{-2}}$ on the main traffic corridors leading into the city center, some of which had AADT flows of up to 41,119 vehicles in 2003.

However, given that less than 5% of grid squares which are intersected by a road have a traffic heat flux greater than 10 $\mathrm{Wm^{-2}}$ (using the grid square area as the source area), it is important to be aware of the negative skew in the traffic emissions data. Mapping the gridded traffic heat flux

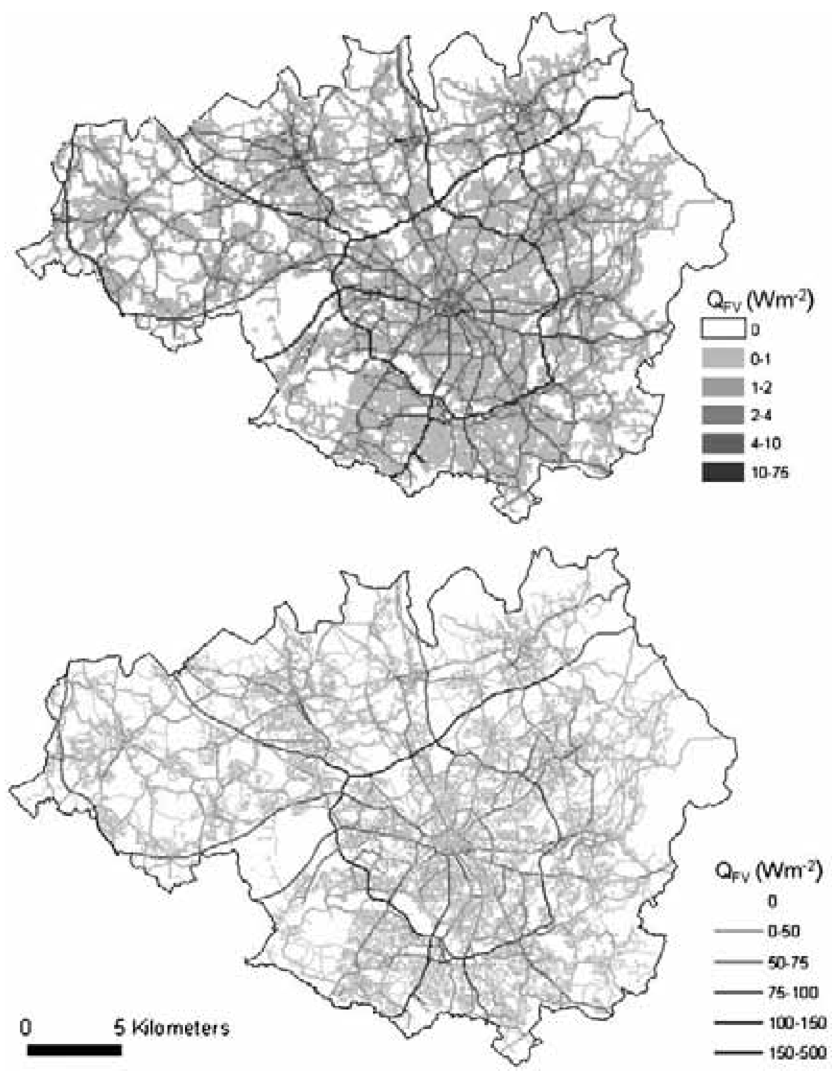


Fig. 4 Daily road traffic heat emissions in Greater Manchester at 200-m grid square resolution for 2003, assuming the source area is the grid square area (*top*) and assuming the source area is the road area (*bottom*). In the bottom figure, minor roads are drawn as *thin lines*, motorways, A roads and B roads are drawn as *thick lines* with *shading* denoting the magnitude of emissions in each square

Table 4 Heat emission factors for the different vehicle types at varying speeds, calculated using the NAEI emissions database (Barlow et al. 2001)

Heat emissions factor (W m^{-1})

Speed kph/mph	2 WMV	Petrol car	Diesel car	Petrol LGV	Diesel LGV	HGVR	HGVA	Bus
16/10	22.01	41.21	38.22	55.35	56.53	162.13	379.78	162.13
32/20	15.60	29.59	28.49	42.19	44.32	120.29	285.07	115.62
48/30	13.16	25.92	24.74	36.27	37.75	108.42	257.98	102.55
64/40	13.34	24.74	23.20	33.43	34.41	104.95	249.41	99.31
97/60	16.47	27.18	26.43	38.89	43.24	121.25	284.84	117.37
113/70	16.80	30.55	31.69	48.57	58.94	131.15	307.03	127.34

estimates clearly illustrates the dominating effect of motorways on overall traffic emissions (Fig. 4), and it is these heavily trafficked roads, which have a substantially higher volume of larger vehicles, that are responsible for localized anthropogenic heating. Table 4 shows derived heat emission factors as a function of vehicle type and speed. These show emissions from HGVs and buses to be substantially greater than cars and in some cases the emissions are an order of magnitude larger. Consequently, motorway traffic is responsible for almost 50% of total daily road traffic heat emissions on a city-scale (Table 5) in spite covering a comparatively small surface area. There are also concentrations of traffic heat emissions in Manchester city center and some of the smaller local authority centers, corresponding to high road flows and densities.

Comparisons with other sources of data provide some confidence that the method used offers a reasonable approximation to the traffic heat flux component. Regional estimates of fuel consumption by the road transport sector produced by Goodwin et al. (2005) attribute 1,409 thousand tons of fuel to Greater Manchester in 2003. In comparison, fuel consumption determined during an intermediary stage of the heat emissions calculations, is just below 1,300 thousand tons for all roads across Greater Manchester. Since heat emissions are assumed to be equal to the energy consumed it is also possible to use BERR aggregate energy statistics to verify the estimated heat emissions (Table 5). The heat emissions, like the fuel data, underestimate the energy consumption data by 7 GWh. There are, however, several reasons for this discrepancy. The BERR data assume Greater Manchester is a discrete entity and imply that all fuel bought in Greater Manchester is also consumed there. However, in reality, fuel bought outside of the region is likely to be consumed within it and, similarly, fuel bought in Greater Manchester may not necessarily be consumed there. If the latter is greater than the former this may explain the deficit in calculated fuel consumption. In addition, the assumed calorific values may underestimate the true efficiency of petrol and diesel, therefore giving rise to lower heat emissions. Similarly, the assumption of constant speed is an oversimplification and there are likely to be periods, such as rush hour, when there is a significant departure from the assumed speeds. Indeed, it has been shown elsewhere that even in 2003 parts of the city's motorway network were already exceeding their Congestion Reference Flows (a measure of the likelihood of congestion on roads during peak periods) (Lindley et al. 2006). While the current emissions are found to be higher at major road junctions this is simply due to the volume of traffic and does not consider the inefficiency of idling traffic, for which fuel consumption and heat emissions are likely to be even higher (Greene 1981). Therefore the traffic heat emissions calculated are expected to be somewhat conservative, particularly so in localities with specific local transport-related sources such as bus stations.

The effects of some of these limiting factors were investigated using sensitivity analysis. Changes to the calorific values of petrol and diesel, which are used to convert fuel consumption to heat output, result in a proportional change to the heat emissions (Fig. 5), but the magnitude of change depends upon road type. Altering the petrol calorific value results in marginally larger changes to the heat emissions across the whole of Greater Manchester compared to an equivalent alteration of the diesel calorific

Table 5 Comparison of the calculated daily traffic heat emissions with estimated daily road traffic emissions using aggregate BERR data for 2003

Estimated heat emissions (GWh)					Energy consumption from road transport (BERR 2004) (GWh)
Motorways	A roads	B roads	Minor roads	Total	
21.51 (49%)	11.42 (26%)	3.76 (9%)	7.18 (16%)	43.87	50.99

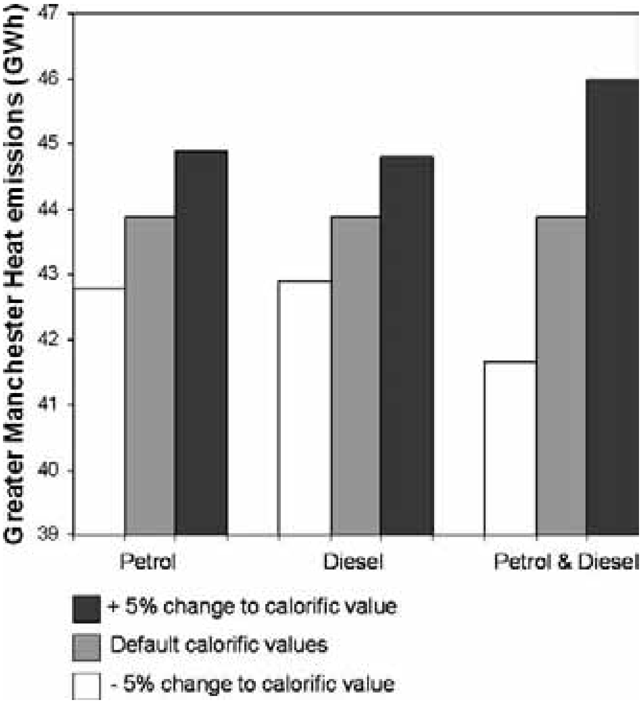


Fig. 5 Effect of changing road transport fuel calorific values on Greater Manchester heat emissions

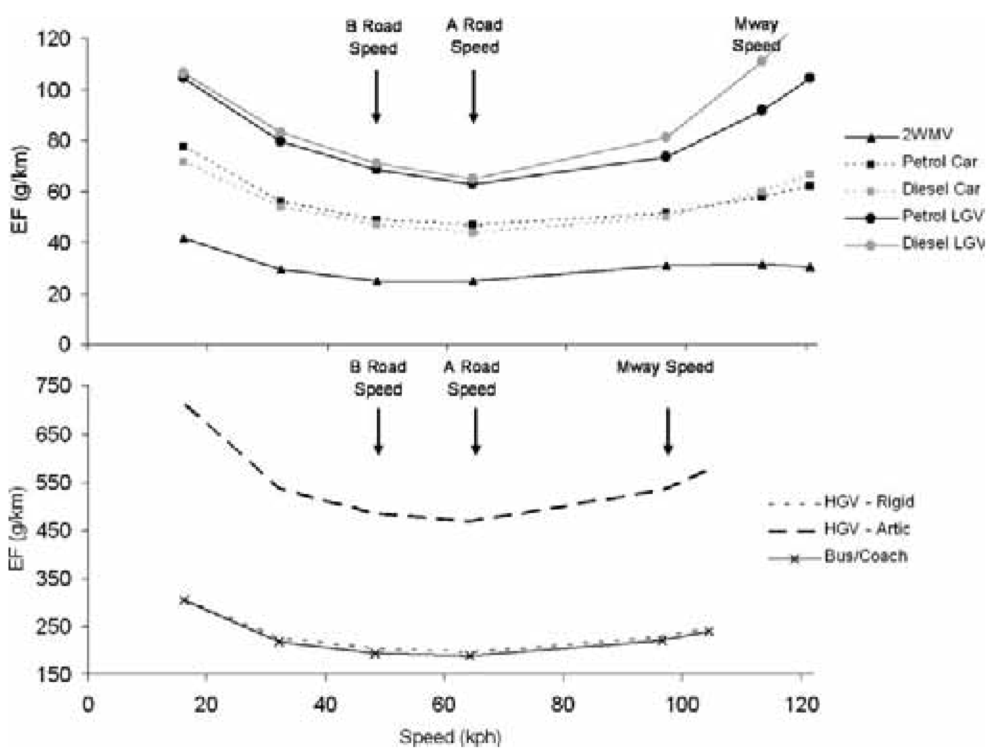
value. However, on motorways the calorific value of diesel becomes more important. An increase in both the petrol and diesel calorific values by 5% to 48.1 and 48.3, respectively, gives overall traffic heat emissions of 46 GWh for Greater Manchester. This is closer to the 51 GWh suggested by the BERR data, which could indicate the original calorific values were too low.

A ± 8 kph (5 mph) change in speed is found to have a relatively small effect (1.8-3.8% change in heat emissions) on a city-wide scale, but can cause a significant localized enhancement of the traffic heat flux. For example, a speed increase of 8 kph (5 mph) was found, in some instances, to increase heat emissions by 100 Wm^{-2} in grid squares containing motorways, a consequence of decreasing fuel efficiency across all vehicles except motorcycles at these higher speeds (Fig. 6). Mirroring the inefficiency of vehicles at high speed, the tendency of the fuel consumption emissions factor is to increase across all fleet types at speeds below 64 kph (40 mph) (Fig. 6), which implies, accordingly, that heat emissions will also be accentuated at very low speeds. This has particular consequences for central areas where typical speeds are as low as 29 kph (17.8 mph) during peak times and 35 kph (21.6 mph) during off-peak periods (DfT 2007). Indeed, an analysis of the central 25 km^2 grid square reveals that estimates of heat emissions in the urban core could be 13% higher, allowing for the reduction in average speed, and up to 22% higher during peak periods.

3.2 Heat emissions from buildings

The maximum emission of heat from buildings for an individual grid square is just over 23 Wm^{-2}, for a square with 43% built surface cover. The highest emissions, as

Fig. 6 Sensitivity of the fuel consumption emissions factor (EF) to vehicle speed



would be expected, are found in town centers, retail zones, and areas associated with manufacturing activity (Fig. 7). The mean building-derived heat flux across Greater Manchester is 3.5 Wm^{-2} but there is considerable variation between grid squares (σ=3.91 Wm^{-2}), as well as between local authorities. Averaged across the local authority, the building heat flux for Manchester is 40% greater than that for the next biggest emitter of heat from buildings, Salford, and over 2.5 times greater than Rochdale, which has the lowest emissions.

To assess the suitability of the 'typical' building energy consumptions (Table 4), the building heat emissions were compared to energy consumption data from BERR (available from: http://www.dti.gov.uk/energy/statistics/regional/index.html). This comparison suggests that the current energy consumption estimates are somewhat conservative, totaling 4, 368, 366 kW across Greater Manchester, accounting for only 80.5% of the BERR energy consumption estimates. In particular, Trafford is considerably under-represented in terms of heat emissions, relative to the BERR energy consumption estimates. Some of the under-representation will be due to the high proportion of land cover associated with manufacturing (10%) which has a wide range of energy consumptions associated with it. In 2005, there were 28 UK Environment Agency licensed industrial processes within Trafford. Most of these were located within the Trafford Park industrial estate, which covers approximately 5 km^2 to the north of the district. In addition to process related heat emissions, there are also many small power plants associated with the area's light manufacturing and engineering firms, although in 2005 there was only one primary combustion plant which was large enough to require licensing. Across Greater Manchester as a whole there are over 100 industrial sites which are monitored by the UK Environment Agency, which are unaccounted for under the current methodological approach for calculating heat emissions. However, it is worth noting that a considerable proportion of the heat associated with industrial facilities tends to be released at a much higher level (typically over 15 m). This means that ground level contributions and localized heating effects are likely to be less than would otherwise be anticipated on the basis of energy data alone.

The majority of the deficit between the BERR energy consumption data and the calculated heat emissions is due to the non-domestic sector. But by increasing the non-domestic typical energy consumptions by a small amount (2%), to account for industrial processes and high energy manufacturing facilities, the total non-domestic energy consumption is estimated to be 57.36 GWh, compared with 60.33 GWh estimated from the BERR data. This scaling up of the heat emissions is considered reasonable as current estimates do not take into account building heights, therefore floor areas are conservatively estimated as the building footprint area. Additional discrepancies between the heat emissions and the energy data are anticipated due to the absence of heat emissions sources associated with non-road transport and industrial processes in the current model.

3.3 Heat emissions from metabolism

The spatial distribution of metabolic heat emissions across Greater Manchester is, at present, limited by the available data, and is therefore restricted to the Census population patterns derived through Surpop data (Martin et al. 1999; Fig. 3). The maximum heat flux from metabolism for a 200-m grid square is calculated to be 7.13 Wm^{-2}. However, the

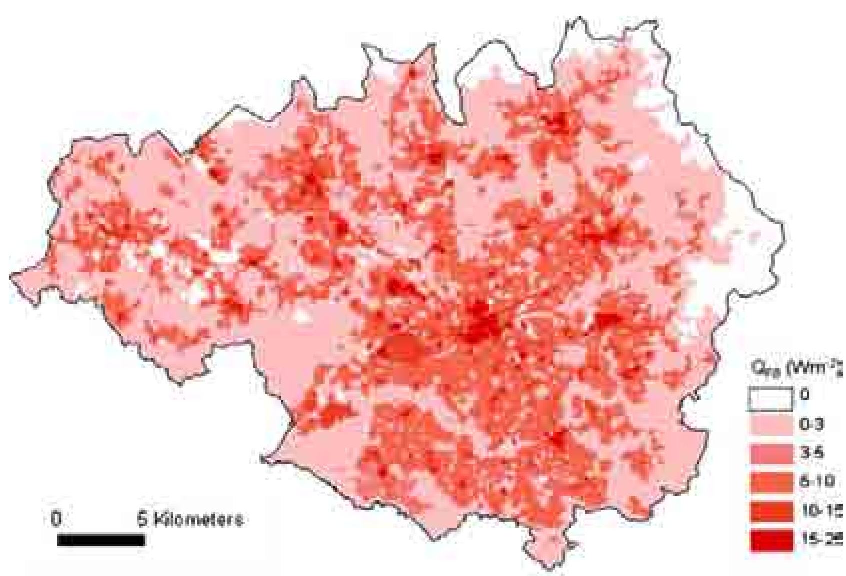


Fig. 7 Building heat emissions at 200-m grid square resolution, calculated using typical building energy consumption values, as given in Table 4

frequency distribution of the metabolic heat flux per grid square, like the distribution of the traffic emissions, is negatively skewed and drops off exponentially toward higher values (Fig. 8), suggesting that this grid square, with a population of 1,392, is unusually high. Indeed, only 28 (<0.1%) of the 33,221 200-m grid squares across Greater Manchester have a population exceeding 1,000. Over 18,000 (54%) grid squares have no allocated population.

There are difficulties associated with using UK Census data to estimate metabolic heat emissions. This dataset is based upon an individual's place of residence, and therefore the areas associated with the highest metabolic heat emissions are those with the highest residential densities (Fig. 9) which are generally found around the periphery of the town centers (Fig. 3). This is particularly evident for Manchester city but also, to a lesser extent, in the satellite towns of Bolton and Wigan. The deficit of people attributed to the town centers is problematic owing to the large proportion of people who commute to work in the city center, and for whom a significant portion of the daily metabolic heat emissions should correspond to their place of work rather than being confined to their home. However, a proportion of the emissions associated with the movement of people throughout the day will be accounted for by the diurnal patterns of building and traffic emissions. In addition, the comparatively low contribution of metabolic heat to overall metabolic heat emissions suggests that the current metabolic emissions are reasonable.

3.4 Total anthropogenic heat flux

The average anthropogenic heat flux across Greater Manchester is 6.12 Wm^{-2} (σ=5.67). A map of the anthropogenic heat flux across Greater Manchester (Fig. 10) highlights the role of Q_F in the development of an urban heat island. Pronounced heat sources are found within the town centers, even when discounting the proportion of metabolic heat emissions that should be attributed to the city center. There is also a dominant heating influence from the heavily trafficked motorways and major A roads. The only areas which are free from anthropogenic heat gain are situated within areas of unimproved farmland, disused and derelict land and rivers/canals, which have very low or no population and no road access. While central areas of Manchester display a higher Q_F than peripheral areas, the heat flux cannot be reliably described by a simple distance decay function due to prominent heat sources associated with roads and satellite towns.

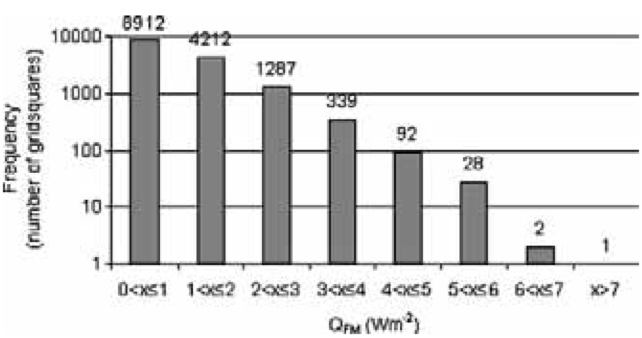


Fig. 8 Frequency distribution of metabolic heat emissions across Greater Manchester (excluding zero-population grid squares)

The proportional split of Q_{FB}, Q_{FV} and Q_{FM} to the total anthropogenic heat flux across Greater Manchester suggests buildings are the dominant emitter of heat, contributing over 60% of Q_F. However, the traffic emissions, which are responsible for just under a third of Q_F, are attributed to a much smaller source area which gives rise to the higher localized heating estimates (i.e., at the resolution of individual grid squares) for traffic compared to buildings. Metabolic energy constitutes around 8% of the total anthropogenic flux, which is in-line with previous estimates. For example, Morita (1993; cited in Ichinose et al. 1999) estimated metabolic heat to be 5-10% of the total in Tokyo.

4 Discussion

Spatial and temporal modeling of the anthropogenic heating profile has an important role in terms of evaluating the potential for harnessing waste heat as an energy source. Anthropogenic heat flux estimates are also necessary for regional climate modeling and have been shown to significantly alter the extent and magnitude of the urban heat island (Betts and Best 2004). The estimates of Q_F for Manchester calculated here are broadly in line with those for London (Mark McCarthy, pers. comm.) and US cities (Sailor and Lu 2004). Detailed analysis of the central Manchester 25-km grid square reveals the surface cover to be 53% urban area (buildings or other impervious). Aggregating the 200×200 m heat emission estimates over the same area, and restricting the source area to that associated with urban-type cover, gives a central anthropogenic heat flux of 23 Wm^{-2}. Similar analysis for central London gives a Q_F of 21 Wm^{-2} (Mark McCarthy, pers comm.). For a less central region of Manchester, the heat flux was 10 Wm^{-2} for a 25-km grid square (assuming 50% urban surface).

However, Q_F does not drop off radially from central Manchester as markedly as appears to be the case in London (Harrison et al. 1984) due to the influencing effect of the smaller satellite towns, and the presence of the outer ring road and other motorways, which generate anomalously high heat emission values some distance from the central conurbation. Comparison at the LA level does suggest central and larger authorities have a higher anthropogenic contribution to the energy balance (Table 6), but the LAs are not really indicative of the radial effect due to

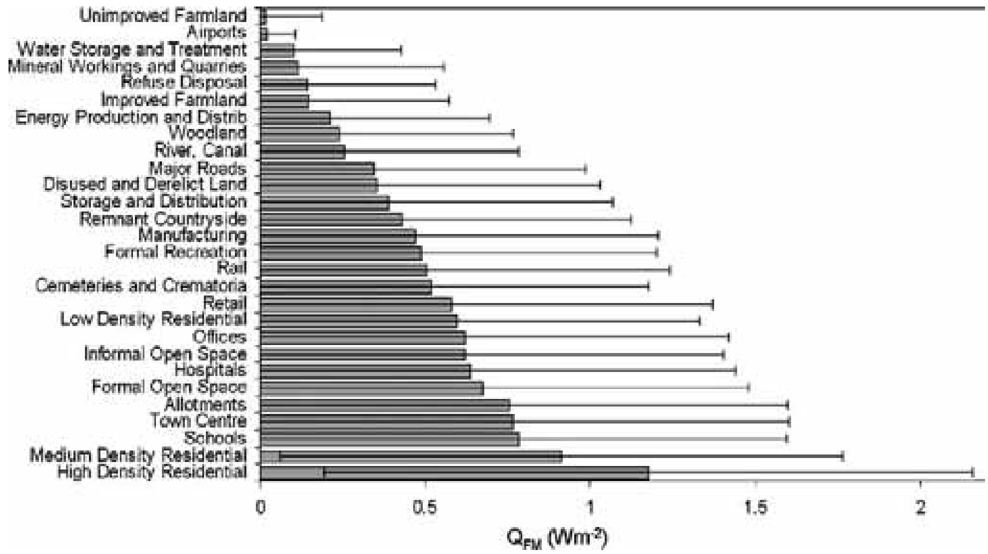


Fig. 9 Mean metabolic heat flux by Urban Morphology Type, shown with ± 1 standard deviation error bar. Note that the use of derived Census data results in low metabolic heat fluxes for 'Town Center', 'Retail' and 'Offices' areas

Manchester LA stretching from the center of the region to the outskirts (Fig. 1).

The daily averaged anthropogenic heat flux estimates (Fig. 10) highlight the potential for exposure to localized heat sources which may lead to additional thermal discomfort and overheating during the summer months, and conversely the potential for lowered energy consumption due to a decrease in heating demand in urban centers during winter. However, it is important to note that the degree to which local heat sources will affect the realization of risks and opportunities at a particular point in space and time will also depend on a range of other factors such as street orientation and prevalent meteorological conditions.

In addition to the spatial distribution of anthropogenic heating, the temporal patterns of heat flux variations are also important for risk and opportunity assessments. Figure 11 displays the seasonal and diurnal variations of Q_F. In the temperate climate of the UK, anthropogenic heating is much higher during the winter, and the magnitude and extent of the anthropogenically forced heat island is greater during this time of year. The evolution of the anthropogenic heating profile throughout the day generally reflects the movement of people into and out of the town and city centers, but the motorway network remains prominent over the course of the day, reinforcing the role of traffic in localized heating.

The seasonal disparities depicted in Fig. 11 are likely to alter under future climate scenarios, with the difference between winter and summer energy consumption reducing as demand for winter space heating declines in favor of summer space cooling. But any consideration of future anthropogenic heating projections should also take into account land use or lifestyle (e.g., greater numbers of people working from home) changes and any policy-driven

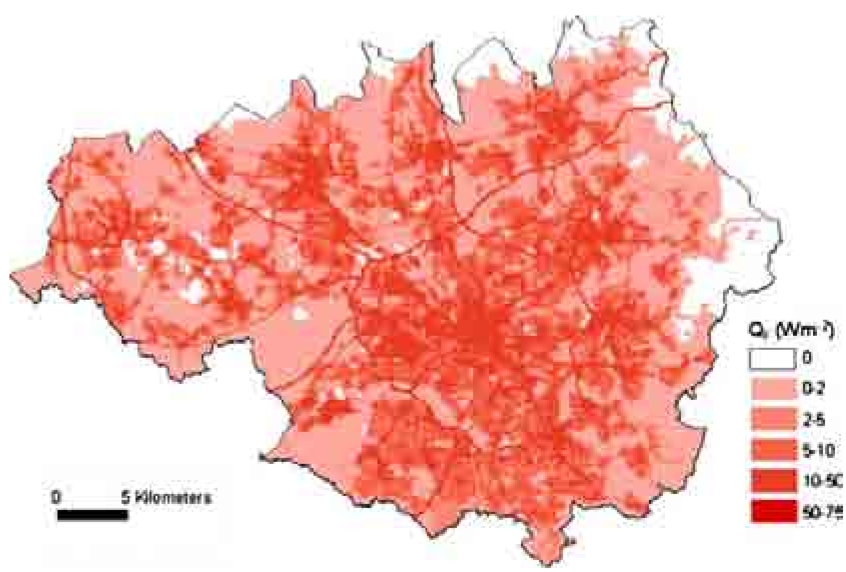


Fig. 10 Total anthropogenic heat flux for Greater Manchester at 200-m grid square resolution

Table 6 Heat emissions by local authority and LA characteristics

LA	Average heat emissions (Wm^{-2})	Average heat emissions (Wm^{-2}) (BERR)	% Greater Manchester heat emissions (W)	Area of major roads (m^2)	Built surface (%)	Population (000s)
Manchester	10.81	11.20	16.78	5,856.77	16.1	437
Salford	8.74	7.54	11.41	8,142.42	11.5	216.4
Trafford	6.86	7.985	9.77	2,530.38	12.0	212.7
Stockport	5.92	5.992	10.02	3,207.87	10.9	282.2
Tameside	5.69	5.756	7.89	2,862.18	9.6	213.7
Bury	5.97	5.765	7.97	3,439.51	9.2	182.1
Bolton	5.06	5.108	9.49	3,366.00	9.2	264.8
Wigan	4.14	4.519	10.47	2,423.62	7.2	218.3
Oldham	3.86	3.840	7.38	4,679.03	7.8	305.4
Rochdale	4.16	4.054	8.82	4,271.95	6.7	206.5
Greater Manchester	6.12	6.18	-	40,779.73	10.6	2,539.1

changes with implications for energy consumption, such as greater use of public transport or energy saving initiatives.

Comparisons between the aggregated heat emission estimates and the BERR energy consumption data suggest that the method outlined above offers a reasonable parameterization of Q_F at the fine-scale spatial and temporal resolution. The tendency for the bottom-up heat emissions to underestimate the top-down BERR energy consumption data has been attributed to conservative estimates of some of the energy parameters, such as the calorific values of petrol and diesel and the typical energy consumption estimates for different building types. Refining these values, through simulation or data collection, may be necessary for future applications of the method.

The approach used here is readily transferable to other UK cities due to its reliance on readily available data. One limitation of the method is that it requires a city to be characterized in terms of land use. This is in itself a potentially time intensive exercise and coupled with the non-static nature of land use this may restrict the longevity and application of the model. However, in the UK there are alternative land use classifications, such as those produced by Cities Revealed from aerial photography analysis (http://www.citiesrevealed.com/). There are also several methods for semi-automating land use classification procedures which are now emerging (e.g., Barr et al. 2004). Indeed, one such method is being developed as part of the SCORCHIO project. These techniques will improve the speed and efficiency with which the method can be applied.

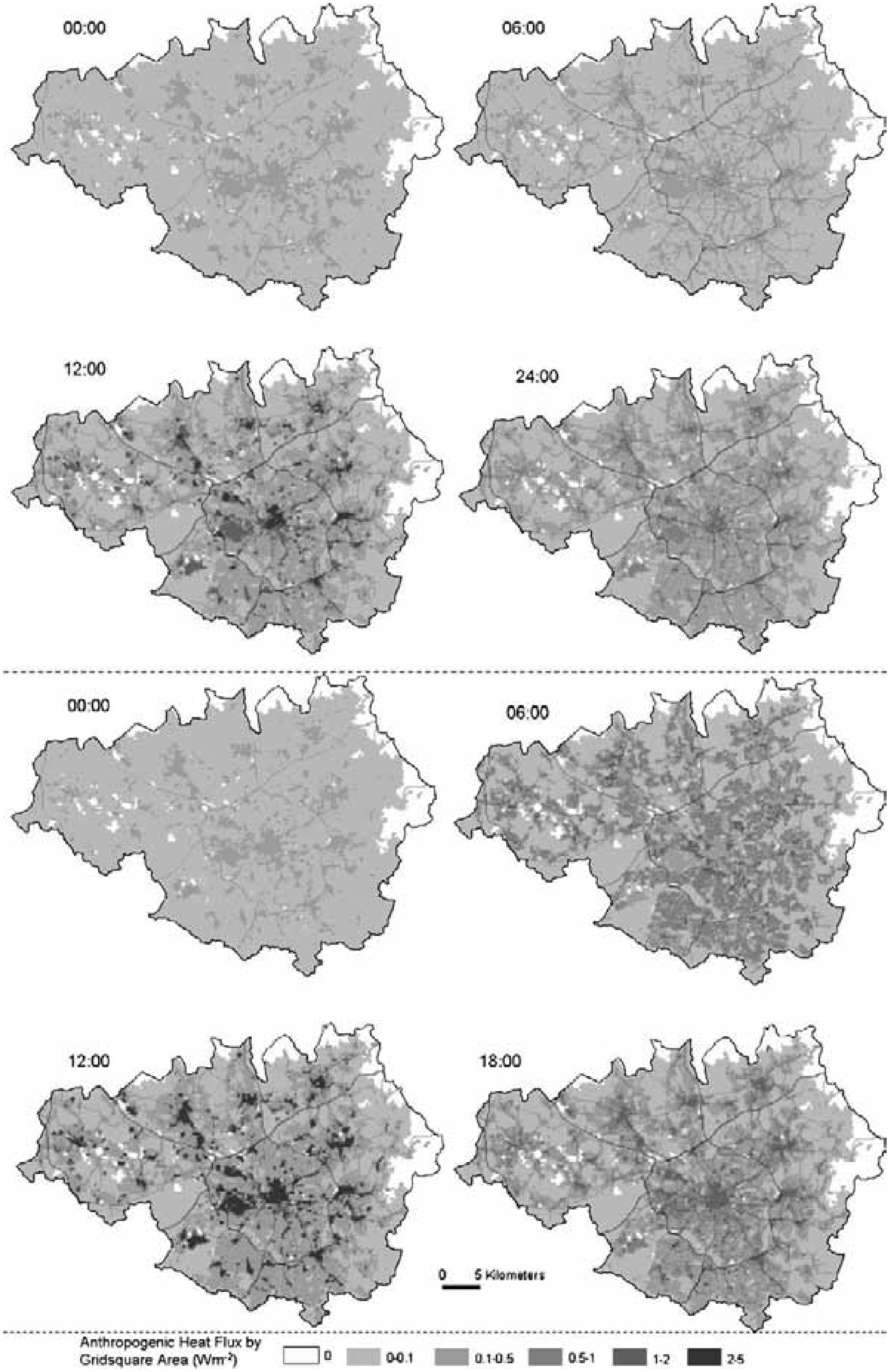
5 Conclusion

A model for estimating the spatial and temporal distribution of anthropogenic heat flux from urban areas has been developed, applied and validated. The work has also allowed the generation of a set of heat emissions factors for transport sources and land use types (Tables 3 and 4).

The model gives a spatially averaged Q_F of 6.12 Wm^{-2} for Greater Manchester as a whole but with emissions of nearer 23 Wm^{-2} in the city center. Very localized estimates (200-m grid square resolution) can reach 75 Wm^{-2} at major junctions of the motorway network. The major road network, along with the situation of several satellite towns limit the extent to which the anthropogenic heat flux in Greater Manchester can be described by a distance decay function, a pattern which may be common in other cities in the UK and elsewhere. The influence of anthropogenic heat emissions is greater during winter when energy consumption in buildings increases due to the demand for space heating. The diurnal patterns of the anthropogenic heat flux, in both winter and summer, match the movement of people. At 06:00, Q_F is highest in residential areas but by midday anthropogenic heat emissions are more concentrated in central areas. During the evening, the heat flux across Greater Manchester becomes more homogeneous as the population returns to the residential areas.

The model has been evaluated to a good accuracy against alternative data for the Greater Manchester area but is found to be sensitive to assumptions about fuel efficiency and non-domestic energy consumption. The model has a tendency to slightly underestimate energy consumptions which are used to compute the heat emissions due to the omission of non-road transport and industrial processes. The omission of industrial processes is likely to have a disproportionate effect in some geographical locations due to the tendency for processes to be located in specific areas. However, the overall effect of heat emissions in these areas is offset to some

Fig. 11 Diurnal patterns of Q_F variation for summer (*top*) and winter (*bottom*) ▶



00:00
06:00
12:00
24:00
00:00
06:00
12:00
18:00
0 5 Kilometers
Anthropogenic Heat Flux by Gridsquare Area (Wm-2)
0
0-0.1
0.1-0.5
0.5-1
1-2
2-5

extent by a proportion of the associated heat emissions being released at height rather than at ground level.

The model is a useful tool which can be used as part of a wider toolkit for determining the urban heat island effect and it can also be used for estimating future anthropogenic heat flux projections for input to climate models. Analysis of heat emissions is important as climate change mitigation policies may reduce CO_2 emissions at the point of energy production but not necessarily heat emissions associated with the end user. This implies that anthropogenic heat emissions will continue to contribute to thermal discomfort and overheating during the summer months.

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