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Global to city scale urban anthropogenic heat flux: model and variability

L. Allen, F. Lindberg and C. S. B. Grimmond*
Environmental Monitoring and Modelling Group, Department of Geography, King's College London, The Strand, London WC2R 2LS, UK

ABSTRACT: The large scale urban consumption of energy (LUCY) model simulates all components of anthropogenic heat flux (Q_F) from the global to individual city scale at 2.5 × 2.5 arc-minute resolution. This includes a database of different working patterns and public holidays, vehicle use and energy consumption in each country. The databases can be edited to include specific diurnal and seasonal vehicle and energy consumption patterns, local holidays and flows of people within a city. If better information about individual cities is available within this (open-source) database, then the accuracy of this model can only improve, to provide the community data from global-scale climate modelling or the individual city scale in the future. The results show that Q_F varied widely through the year, through the day, between countries and urban areas. An assessment of the heat emissions estimated revealed that they are reasonably close to those produced by a global model and a number of small-scale city models, so results from LUCY can be used with a degree of confidence. From LUCY, the global mean urban Q_F has a diurnal range of 0.7–3.6 W m^{-2}, and is greater on weekdays than weekends. The heat release from building is the largest contributor (89–96%), to heat emissions globally. Differences between months are greatest in the middle of the day (up to 1 W m^{-2} at 1 pm). December to February, the coldest months in the Northern Hemisphere, have the highest heat emissions. July and August are at the higher end. The least Q_F is emitted in May. The highest individual grid cell heat fluxes in urban areas were located in New York (577), Paris (261.5), Tokyo (178), San Francisco (173.6), Vancouver (119) and London (106.7). Copyright © 2010 Royal Meteorological Society

KEY WORDS urban climate; anthropogenic heat flux; global climate model; energy balance; metabolism

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1. Introduction

Waste heat produced by human activities is one contributor to the urban heat island (UHI). While this anthropogenic heat flux varies spatially and temporally (diurnally, seasonally and yearly) (Lee *et al*., 2009), under certain conditions it can exceed energy receipt from net all-wave radiation. Typical values range from 20 and 70 W m^{-2} (Crutzen, 2004) but values greater than 1000 W m^{-2} under extreme localized conditions have been calculated, for example in the densest part of Tokyo at the peak of air-conditioning demand (Ichinose *et al*., 1999). However, commonly the flux is omitted from climate models despite its local importance (Fan and Sailor, 2005). Sources include heat generated by the combustion process in vehicles, heat created by industrial processes, the conduction of heat through building walls or emitted directly into the atmosphere by air-conditioning systems, and the metabolic heat produced by humans (Sugawara and Narita, 2009).

Predictions of human induced climate change suggest increases in surface air temperatures anywhere between 0.5 and 6.5 °C over the next 100 years (IPCC, 2007). The UHI effect tends to exacerbate further such warming and temperatures in cities are predicted to rise even more resulting in increased energy demand for cooling systems in the warmest months in cities located in the low and mid-latitudes, although cities in high latitudes may need less heating energy during the cold periods (Taha, 1997). A model of the air-conditioning related heat flux in Tokyo estimated the air temperature already was raised by around 1 °C (Kikegawa *et al*., 2003). As the vast majority of urban agglomerations are situated in the low and mid-latitudes (mostly in the Northern Hemisphere), overall a warmer climate will lead to increased energy consumption, more air pollution and greater risk of human mortality in cities (Jin *et al*., 2005; Smith and Levermore, 2008). A positive feedback cycle has been created in many urban areas, where higher temperatures result in more energy being used for cooling, which in turn add to heat emissions into the atmosphere and raise temperatures further (Crutzen, 2004). It is expected that without UHI mitigation measures energy demand and temperatures will continue to increase during the warmest months.

Anthropogenic heat flux estimates are needed for all cities globally to be able to document the magnitude of effects and so that the impact of the flux can be included in global or regional scale climate modelling. The objectives of this paper are: (1) to develop a model

* Correspondence to: C. S. B. Grimmond, Environmental Monitoring and Modelling Group, Department of Geography, King's College London, The Strand, London WC2R 2LS, UK.
E-mail: Sue.Grimmond@kcl.ac.uk

of global anthropogenic heat flux which allows for fluxes to vary according to the time of day, time of year and location; (2) to evaluate the performance of the model across a range of scales; and (3) to investigate the size of the global urban anthropogenic heat flux. Sailor (in press) noted the current limitation to coarse spatial and temporal resolution at the global scale. Here we present an open-source global model with improved spatial (2.5 × 2.5 arc-minutes) and temporal resolution (hourly) to that currently available.

2. Anthropogenic heat flux modelling

Anthropogenic heat generated in urban areas has been modelled for a number of cities around the world. Estimates have generally provided a horizontal grid, sometimes with a vertical third dimension. The resolution has ranged from 100 m^2 cells (Grimmond, 1992; Pigeon *et al*., 2007), to 200 m^2 (Smith *et al*., 2009), to 250 m^2 (Ichinose *et al*., 1999). Klysik (1996) and Sailor and Lu (2004) estimated emissions at a local area level, using variable cell sizes based on land use polygons. Others have focused on an individual city block, taking into account the geometry of buildings and the temperature change at different heights above the ground surface (Kondo and Kikegawa, 2003).

At the other extreme lower resolution grids have been used to examine larger areas. For example Makar *et al*. (2006), based on several global datasets but centred on North America, at a scale of about 15 km^2 and Flanner (2009) created a global model which had 0.5° × 0.5° cells (3091 km^2 at the equator). Flanner (2009) estimated the heat flux over all land areas without discriminating urban from rural land uses. The heat input of individual cities would have been greatly underestimated because of the size of the grid cells, so local high anthropogenic heat fluxes in urban areas could not be examined using this model.

The majority of models are based upon a simple partitioning of the sources of the anthropogenic heat flux (Q_F) (Grimmond, 1992; Sailor and Lu, 2004):

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

where Q_V is heat from vehicle emissions, Q_B is heat released from buildings, and Q_M is human metabolic heat. It is not possible to directly measure Q_F (Grimmond, 1992) although recently it has been determined as a residual of the urban energy balance (Offerle *et al*., 2005; Pigeon *et al*., 2007). Most estimates are based on assessment of the three components in (1). However some have omitted Q_M as it may be as little as 2–3% of Q_F (Sailor and Lu, 2004). Alternatively other studies have focused mainly on Q_B as this usually makes up the majority of Q_F (e.g. Hamilton *et al*., 2009).

Here energy consumption is assumed to be equivalent to anthropogenic sensible heat. In addition to this there is a latent heat component from large commercial buildings which have evaporative cooling in cooling towers for air-conditioning load (e.g. Moriwaki *et al*. 2008; Sailor in press). At the design condition a cooling tower can remove up to 80% of the internal loads through evaporative cooling (Sailor, in press). Thus in mega-cities with tall towers (e.g. Tokyo) in the summertime there will be areas where this anthropogenic latent heat is important (Moriwaki *et al*., 2008, see their Figure 7).

2.1. Metabolic heat emissions

Humans continuously release heat because of metabolic processes (Sailor and Lu, 2004). Treatment of Q_M varies from non inclusion because of its relatively small contribution to total Q_F (Pigeon *et al*., 2007); to documentation of the term (e.g. Lee *et al*., 2009); to not explicitly including it (e.g. Flanner, 2009). Ichinose *et al*. (1999) did not incorporate Q_M into a model of Tokyo because it was too complex to map, although it was later recognized that this omission, amongst other excluded elements, contributed to an underestimation of Q_F (Sugawara and Narita, 2009).

Estimates of Q_M commonly are based upon population statistics. For example, fine-scale census data were used for Vancouver (Grimmond, 1992) and Manchester (Smith *et al*., 2009), although the UK census information used for Manchester was gathered in 1991, 18 years earlier than the year of publication of the study. Sailor and Lu (2004), for USA cities, used census data but allowed population density to vary over space and time. Makar *et al*. (2006) used a global population density grid with a 2.5 × 2.5 arc-minute resolution.

Metabolic heat emissions are determined from the population data with an assumption of average human metabolic rate. The metabolic process is known to vary with human activity, with the average person emitting heat around 70 W when asleep, and up to 800 W when undergoing strenuous exercise (Smith *et al*., 2009). Models have assumed a constant rate of 100 W per person (Makar *et al*., 2006), which does not take account of diurnal variability, or have a defined diurnal cycle (Grimmond, 1992; Sailor and Lu, 2004; Smith *et al*., 2009). Sailor and Lu (2004) assumed constant with time of year metabolic rates that at night was (between 2300 and 0500) 75 W per person, and in the daytime (between 0700 and 2100) was 175 W per person, with transitional values for the hours in between. The same time periods were implemented by Smith *et al*. (2009), although the night value was 70 W and the daytime average was 250 W. Grimmond (1992) split each day into two parts (night values 2300–0700; day 0700–2300).

2.2. Vehicle heat emissions

Fuel combustion is the main source of heat from motor vehicles (Pigeon *et al*., 2007). Clearly there is a strong diurnal cycle to traffic, which is well documented in traffic count data, with peaks in the morning and early evening. This is included in a number of models (Sailor and Lu, 2004; Lee *et al*., 2009; Smith *et al*., 2009). As with Q_M, patterns in traffic generally do not vary between seasons (Sailor and Lu, 2004).

A much broader range of methods have been used to calculate Q_V than for Q_M which includes both bottom-up and top-down approaches. In some countries information on the distance that vehicles are driven every day is collected, and these statistics have often been used in models. Sailor *et al*. (2007) used average distance travelled per person for USA cities, to calculate total vehicle distance from population data, with a diurnal cycle from hourly traffic counts applied with the values located on the roads within the grids for various cities. Sailor and Lu (2004) also applied this bottom-up approach, recommending the use of a diurnal profile based on Hallenbeck *et al*. (1997) as a top-down method when detailed traffic data are not available. This accounts for different patterns on weekends and weekdays. Lee *et al*. (2009) used travelling distance statistics, but they were calculated per vehicle so the numbers of registered vehicles in the area are also needed.

One of the most comprehensive bottom-up approaches to modelling Q_V was used for Manchester by Smith *et al*. (2009). Detailed traffic count data, which recorded the average traffic density on different types of roads (major, minor, motorway), the types of vehicles (motorcycles, cars, buses and large goods vehicles) and fuel type (petrol and diesel) were used. Once the numbers of vehicles and travel distances were allocated spatially (for this and other models), the value of Q_V is estimated with assumptions about fuel consumption, depending on average speed, fuel economy, and fuel type.

Values for the amount of energy released from fuel combustion include: 45.85 kJ g^{-1} for petrol and 46 kJ g^{-1} for diesel in the UK (Smith *et al*. 2009); 43.8 kJ g^{-1} for petrol and 42.5 kJ g^{-1} for diesel in France (Pigeon *et al*., 2007); while an average of 45 kJ g^{-1} over an entire fleet has also been used (Sailor and Lu, 2004; Sailor *et al*., 2007). Unlike the previous models, Lee *et al*. (2009) estimated fuel emissions on the volume (an average of 34.3 MJ l^{-1}) instead of the mass of fuel.

Top-down approaches have used annual energy consumption values for the transport sector, which are distributed across the year with diurnal and seasonal cycles, then mapped to the roads within the grid assuming uniform Q_V for every road (Ichinose *et al*., 1999).

2.3. Building heat emissions

Top-down and bottom-up approaches to Q_B, also have been used (Heiple and Sailor, 2008). Annual energy consumption statistics over a large area are often used in the top-down approach, which are then distributed over the year according to time and season; while bottom-up methods use much finer scale energy data (usually hourly) for single buildings, which are scaled up based on the number of buildings (Lee *et al*., 2009).

The building heat emissions comprises of stationary or fixed sources. It has been sub-divided in some models into: sectors (industrial, commercial and residential; residential and non-residential) (Pigeon *et al*., 2007; Hamilton *et al*., 2009) and fuel types (electricity, other building heating) (Sailor and Lu, 2004). The highest resolution models use records of hourly energy consumption in buildings or annual energy consumption over very small areas. Top-down low resolution approaches utilize annual energy consumption totals.

Bottom-up methods have used land use grids or floor space statistics converted into heat emissions. For example, Smith *et al*. (2009) applied two different diurnal and seasonal cycles based on whether the land use was domestic or non-domestic; and Sailor *et al*. (2007) used groups of buildings with similar characteristics and floor space with time dependent diurnal and seasonal profiles for each building category.

Data from countries (Flanner, 2009), states (Sailor and Lu, 2004), and other statistical areas (Hamilton *et al*., 2009) have been used to create city wide to 1 km^2 grids estimates to which daily and seasonally cycles are applied. For example, Flanner (2009) used country-level annual totals of consumption of non-renewable energy and distributed by population density (a technique also used by Makar *et al*., 2006). The amplitude of the annual cycle, based on day of year and latitude, increases with distance from the equator and the same diurnal cycle, based on Sailor and Lu (2004), is used for every location. Ichinose *et al*. (1999) distributed annual energy data, using diurnal and seasonal cycles as function of building height and business type.

The timeliness of data is important as changes in technology result in changes in energy use. Widespread computer use and advances in technology such as mobile phones and personal music players (which have to be charged directly from an electricity supply rather than use disposable batteries) have meant that energy consumption will have increased, especially in the richest countries.

A key assumption often made in models of Q_F is that no time lag exists between energy consumption and emitted heat, because detailed information about the ventilation system and fabric of buildings would be needed to estimate the time delay (Smith *et al*., 2009). Heiple and Sailor (2008) compared two approaches in estimating Q_B in Houston over grids with the same scale, which revealed that bottom-up calculations produced a time lag that led to later peaks in heat emissions than in the top-down approach. While average values of Q_B over the city differed by less than 3% between the two methods, bottom-up methods showed much more spatial variation and peak values up to 20 times greater (Heiple and Sailor, 2008).

Q_F is strongly affected by climate, because this determines whether heating or cooling systems are used. Between 60 and 70% of energy consumption in buildings is used for heating, air-conditioning and water heating in the USA (Heiple and Sailor, 2008). Understanding what temperature people feel comfortable at inside buildings (which determines energy use), and how the outdoor temperature is linked to this thermal comfort, is a critical

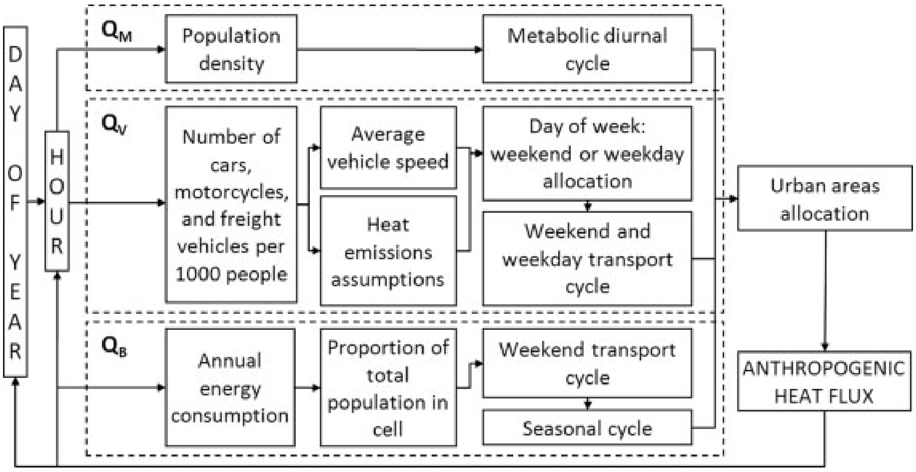

Figure 1. Flowchart of the LUCY global anthropogenic heat model.

part of these assumptions. Monthly average temperatures can be used as a measure of thermal comfort (Nicol and Humphreys, 2002), and has been implemented in a model by Klysik (1996) where energy use was scaled according to the outdoor temperature.

The temperature often used as the most comfortable internal building air temperature is 18 °C (Klysik, 1996). The outdoor temperature which naturally produces this internal temperature in buildings is known as the 'balance point', because the climate-dependent energy demand is lowest at this point (Amato *et al*., 2005). As the outdoor temperature increases or decreases, heating or cooling energy is needed and energy consumption increases proportionately with temperature (Ruth and Lin, 2006). This balance point may vary between residential and commercial sectors. Amato *et al*. (2005) estimate the monthly outdoor temperature of 15.5 °C is the balance point for residential buildings, and about 12.75 °C for commercial buildings.

3. Methods

In this study, a model [large scale urban consumption of energy (LUCY)] of global anthropogenic heat was developed based on Equation (1) at 2.5 × 2.5 arc-minute resolution (about 21 km^2 at the equator) using the WGS84 datum with the latitudinal extents stretching from 85°N to 58 °S. This was chosen as it is the highest resolution population density dataset (CIESIN, 2005a) available at a global scale. Where possible, data were collected for 2005, to allow comparison with the global results by Flanner (2009). Flanner's (2009) global model apportioned energy by population density, but did not specifically include traffic emissions and metabolic heat. Here all three components of Q_F are included (Figure 1) as described in the following.

3.1. Metabolic heat

Metabolic heat (Q_M) emission was calculated using:

$$Q_M = \frac{PH_M}{A \times 10^6} \quad (2)$$

where P is the number of people in each grid cell, A is the area of each grid cell (km^2), and H_M is the amount of energy released per person as a function of hour of the day (W). The cell size is multiplied by 10^6 to convert W km^{-2} into W m^{-2}. The population data (CIESIN, 2005a) were converted to density for areas of 2.5 arc-minute resolution using the latitudinal and longitudinal bounds:

$$A = (\alpha_2 - \alpha_1)(\sin\delta_2 - \sin\delta_1)(6378.135\ \text{km})^2 \quad (3)$$

where α_1 is the western longitude of the grid cell, α_2 is the eastern longitude, δ_1 is the southern latitude and δ_2 is the northern latitude, and 6378.135 km is the radius of the Earth (Matney, 2008).

The diurnal cycle of metabolic emissions (H_M), followed Sailor and Lu (2004), with 75 W as a minimum, 175 W at the maximum, and a transition value of 125 W. For each of the 231 countries and external territories in 2000 in the world (CIESIN, 2005b) the normal business hours were taken to reflect the times when most people would be active. Most of the information was collected from travel websites (Table I), although it proved difficult to find this for some countries, especially North Korea, where only a report by UNHCR (2006) about total weekly working hours in a factory was found. Countries were categorized based on these typical work hours and the different diurnal patterns applied (Table II). In the current version the difference in average calorific intake, and hence metabolic heat release which varies substantially from developed to developing countries is not taken into account.

Although it is quite possible that the majority of people will remain within the boundaries of each cell for most of a day, there will inevitably be movement between cells, especially where populations are distributed near cell boundaries. The pattern of commuting into cities on weekdays, especially in more developed countries, may also inflate day-time populations. As decisions could not be made about whether there would be a net increase or decrease in population for each individual cell no inter-cell movement was incorporated.

Table I. Data used in the LUCY model.

Heat source	Input	References	Spatial/administrative unit
Metabolic heat	Population density	CIESIN (2005a, 2005b)	Global 2.5 arc-minute grid
	Normal business hours	Lonely Planet (2009)	American Samoa, Azerbaijan, Bhutan, Bosnia-Herzegovina, Cyprus, East Timor, Ecuador, Equatorial Guinea, Grenada, Guam, US Virgin Islands
		Frommer's (2009)	Egypt
		CAC Biodiversity (2003)	Kazakhstan
		Ile Mayotte (2007)	Mayotte
		UNHCR (2006)	North Korea
		Saint Pierre et Miquelon Info (2009)	St Pierre and Miquelon
		World Travel Guide (2009)	All other countries and territories
Vehicle heat	Vehicles density and types	Worldmapper (2006a)	All countries and territories
	Fixed public holidays	World Travel Guide (2009),	All other countries and territories
		Q++ Studio (2009)	Mayotte, St Pierre and Miquelon
	Weekend days	Bank Holidays of the World (2009), Lonely Planet (2009), World Travel Guide (2009)	All countries and territories
	Daily vehicle pattern	Hallenbeck *et al.* (1997, p. 25)	All countries and territories
	Vehicle heat emissions	Smith *et al.* (2009, p. 27)	All countries and territories
Building heat	Primary energy consumption	EIA (2009)	All countries and territories except for
	Electricity consumption	CIA Factbook (2009)	Anguilla, Jersey, Mayotte, Northern Mariana Islands
		States of Guernsey (2008)	Guernsey
	Electricity production	Worldmapper (2006b)	Andorra, Liechtenstein, West Bank and Gaza Strip
	Temperature data	Willmott *et al.* (1998)	Global 0.5° × 0.5° grid

Table II. Metabolic heat patterns.

Active metabolic period (75 W)	Night metabolic period (175 W)	Number of countries with same pattern	Example country/region
7 am to 9 pm	11 pm to 5 am	87	United Kingdom
6 am to 9 pm	11 pm to 4 am	82	Ghana
6 am to 8 pm	10 pm to 4 am	30	Germany
7 am to 8 pm	10 pm to 5 am	15	Colombia
6 am to 7 pm	9 pm to 4 am	10	Albania
5 am to 7 pm	9 pm to 3 am	6	Congo
7 am to 7 pm	9 pm to 5 am	1	Svalbard

3.2. Vehicle heat

Limited data are available for vehicle numbers at a global scale. The most recent information obtained was the average number of cars, motorcycles and freight vehicles (including buses) per 1000 people, from data originally collated in 2002 in the IRF World Road Statistics (Worldmapper, 2006a). Vehicle heat emissions (Q_V, W m^{-2}) were calculated using:

$$Q_V = \frac{[V_C E_C + V_M E_M + V_{FR} E_{FR}]F \times 24 \times PDH_W}{A \times 3.6 \times 10^{12}} \qquad (4)$$

where V_C is the number of cars per 1000 people, V_M is the number of motorcycles per 1000 people, V_{FR} is the number of freight vehicles per 1000 people, E_C, E_M, and E_{FR} are the emissions factors for the three types of motor vehicle, dependent on speed (W m^{-1}), F is a multiplying factor to change the total number of vehicles, D is the distance travelled over an hour (m), and H_W is the hourly fraction of the daily total of vehicles. The hourly number of vehicles was multiplied by 24 to give the daily maximum vehicles total. Conversions are needed for the area to obtain W m^{-2}; the division of population by 10^3 to calculate the correct vehicle numbers; and the division of the hourly total by 3600 (s) to get the average hourly heat emissions.

Smith *et al.* (2009) emission factors were applied to the vehicle groups, as they provide information about heat emissions for different vehicles types and at varying

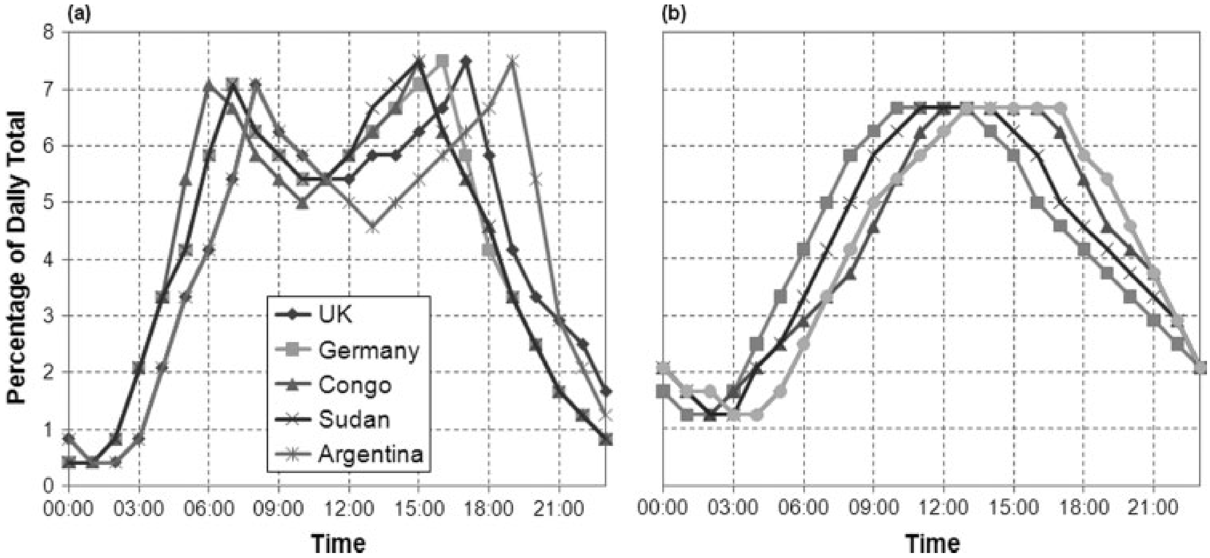

Figure 2. Five countries diurnal curves of vehicle usage for: (a) weekday and (b) weekend based on normal work and non-work habits.

speeds. Here the values for petrol cars were chosen rather than diesel, because it was assumed that most cars use petrol. More than 80% of cars are fuelled with petrol in the UK (Smith *et al*., 2009), and Sailor and Lu (2004) used a petrol-based emissions value for their model.

In LUCY traffic was limited to 64 km h^{-1} because average urban area speeds were unlikely to be higher than this, but in future modelling other speeds could be used.

The diurnal cycle of vehicle numbers depends on whether the day is a weekday, weekend, or public holiday. A database of fixed public holidays (those the date does not change from year to year) was assembled for all countries, the majority of information from World Travel Guide (2009). While most countries in the world consider Saturday and Sunday as the weekend, some follow a Thursday/Friday or Friday/Saturday weekend pattern (Table I). Some holidays, for example, Easter, do though vary from year to year.

The diurnal traffic patterns through the week were based on Hallenbeck *et al*. (1997). Weekday peaks were timed to coincide with the normal working hours for each country, with morning and evening peaks at 7.1 and 7.5% of total daily traffic respectively (Figure 2a). Weekend total traffic volumes were assumed to be 20% less than at weekdays (Hart and Sailor, 2009). The traffic patterns were more spread through the day, and were loosely based on working hours (Figure 2b). H_W accounts for whether each day was a public holiday or weekend day in each country to apply the relevant diurnal cycle and weekend reduction factor.

3.3. Building heat

Total primary energy consumption statistics for each country were used to calculate building heat emissions. Data for 2005 from EIA (2009) were converted from BTU into kWh. Electricity consumption or production was used for a few small countries where EIA data were not available (Table III) resulting in probable underestimation for these areas as oil and gas consumption was ignored. The heat emissions from buildings (Q_B, W m^{-2}) were estimated with:

$$Q_B = \frac{EPH_E T_F}{P_T A \times 8.76 \times 10^6} \quad (5)$$

where E is the total net energy consumption (kWh), H_E is the hourly energy use, T_F is an energy use scaling factor based on typical monthly temperature, and P_T is the total population in the country which the grid is located. H_E was based on the weekend pattern for vehicles, because energy consumption has a similar diurnal cycle (Smith *et al*., 2009). A grid of total population was calculated by summing the population within each country using

Table III. Countries with missing data.

Traffic (vehicle heat)	American Samoa, Anguilla, Aruba, Bermuda, British Virgin Islands, Cayman Islands, Faeroe Islands, Falkland Islands, French Guiana, French Polynesia, Gibraltar, Guadeloupe, Guam, Guernsey, Isle of Man, Jersey, Macao, Martinique, Mayotte, Montserrat, Netherland Antilles, New Caledonia, Norfolk Island, Northern Mariana Islands, Pitcairn, Reunion, Saint Helena, Saint Lucia, Saint Pierre and Miquelon, Svalbard, Tokelau, Turks and Caicos Islands, Wallis and Futuna, United States Virgin Islands
Energy consumption (building heat)	Isle of Man, Marshall Islands, Federated States of Micronesia, Monaco, Norfolk Island, Palau, Pitcairn, San Marino, Svalbard, Tokelau, Tuvalu, Timor-Leste, Wallis and Futuna

the global countries grid. The energy data are multiplied by 1000 to obtain watt-hours and then divided by the number of hours in the year (8760).

To calculate T_F the mean monthly temperature was used relative to a balance point (Ruth and Lin, 2006). The highest resolution global monthly average temperature data set available, $0.5^\circ \times 0.5^\circ$ (Willmott *et al.*, 1998), were regridded to 2.5 arc-minutes while maintaining the same values as the original grid. Nicol and Humphreys (2002) found that the thermally comfortable building temperature of 18 °C in naturally ventilated buildings was present at a mean monthly temperature of 12 °C, so this temperature was chosen as the balance point with a multiplication factor of $T_F = 0.7$. Energy demand increases in the coldest months (Amato *et al.*, 2005), so with a decrease of 1 °C, energy consumption was assumed to increase by 5%. Air-conditioning in the hottest months was taken into account by increasing the multiplication factor by 3% with every 1 °C increase, as determined by Kondo and Kikegawa (2003). Average monthly temperatures led to the annual totals of energy consumption used LUCY deviating by varying amounts from the EIA information. This was addressed by capping the energy increase at −4 and 35 °C (reverting back to a factor of 1); however there was still underestimation of energy consumption in the higher latitudes and some overestimation in low latitudes. The urban area average was about 96% of the EIA statistics, so this component was accepted for use in LUCY.

3.4. Anthropogenic heat flux model

Matlab (version R2009b) from Mathworks Inc. are used to calculate the global distribution of all three components of Q_F. Results can be calculated for a single day or a sequence of days (Figure 1). New data can be added to the model by the user. The analysis presented here is based on 2005. The model can be run at two spatial extents (1) global (LUCY) or (2) individual urban areas (LUCYcity).

There are a number of caveats associated with the application of the model or its current form. Individual hours can be compared globally but currently time zones are not explicitly included so an exact snapshot of anthropogenic heat across the world at any hour is not produced. For some countries, mostly islands, it was not possible to acquire all data. These likely have only a very small contribution to global anthropogenic heat. Transport related data are missing for more countries than building energy data (Table III). Electricity consumption data are used instead of total energy consumption for some countries (Table III). Population densities are more accurate in more developed countries as more recent finer scale data are available.

While it is possible to generalize working or energy consumption patterns within countries, the characteristics of urban areas may vary especially in the largest countries such as the USA or Russia, where urban climate effects at local scales may change the regional climate significantly. The balance point assumption has a large influence on anthropogenic heat emissions, and relies explicitly on thermal comfort levels of people according to outdoor temperatures (see Section 3.3). This can lead to some seasonally inaccurate estimates of heat flux in the model (such as in Tokyo). Inclusion of finer scale temperature data and monthly energy loads would allow improved balance point in different countries.

Traffic counts may prove more reliable to estimate Q_V than the number of cars owned, which do not indicate how many are actually driven each day. Daily and hourly traffic totals could be used to calibrate the ownership dataset for cities or countries, and also make the weekday and weekend curves for individual cities more accurate. This type of data could be added in future versions of the model. Here one average vehicle speed is used for all urban areas in the world. Emissions factors and the fleet composition (petrol or diesel vehicles) were mostly based upon UK data. However this could be altered by a user. An improved model would allow for variability in vehicle speeds between countries, and look at the fleet composition and heat production from vehicles in different countries. The use of average speed underestimates emissions, where vehicles are stopped at traffic signals, especially magnified during peak traffic hours (Smith *et al.*, 2009). Estimates could be improved by incorporating a diurnal cycle of emission factors associated with different efficiencies of engines due to traffic congestion.

4. Global anthropogenic heat flux

LUCY is designed for diurnal, seasonal variations of global anthropogenic heat emissions at a high spatial resolution. Global average heat flux for each hour of the year was not modelled (although could be) rather selected days from each month. LUCY was run for a number of days throughout the year (2005), with the assumption of an average vehicle speed of 48 km h^{-1} and a vehicle multiplication factor (F) of 0.8 (80% of total vehicles are mobile). One weekday (Monday–Wednesday for all countries) and one weekend day (either Saturday or Sunday following the prevailing pattern around the world) are modelled for each month of the year. Days where no countries had public holidays are chosen, so that a fair comparison could be made between months. The output from the model covering a part of Europe is shown in Figure 3.

It is not possible to evaluate LUCY's Q_F with real measurements spatially, due to difficulties in measuring this heat flux (Offerle *et al.*, 2005; Pigeon *et al.*, 2007), so the results are compared with estimates from other models. The results of mean annual Q_F from LUCY for 2005 are aggregated to match the resolution produced by Flanner (2009). Only urban areas are compared as rural areas have Q_F values which are almost zero. The mean difference between the two models is 0.046 W m^{-2} and the standard deviation is 0.629 W m^{-2}. A pixel

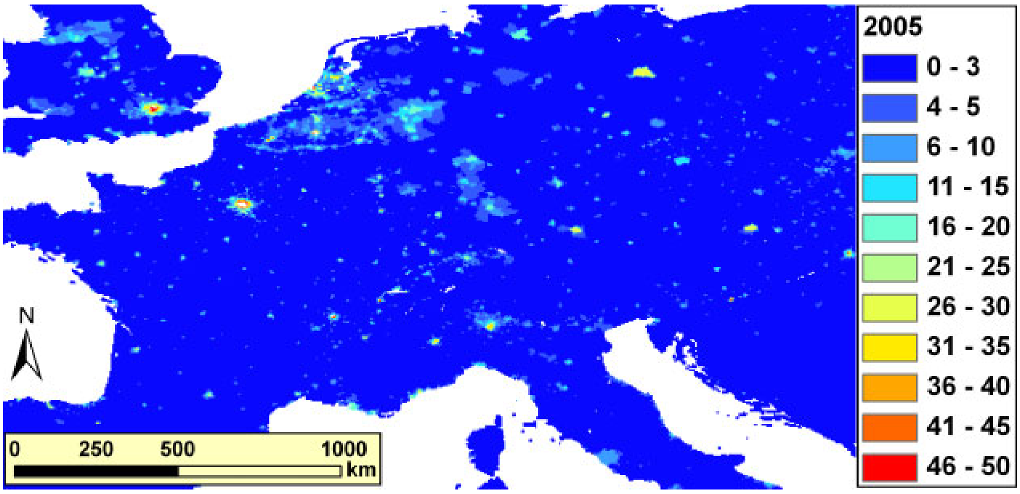

Figure 3. Annual average Q_F (W m^{-2}) across Central Europe in 2005. The pixel resolution is 2.5 × 2.5 arc-minutes. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

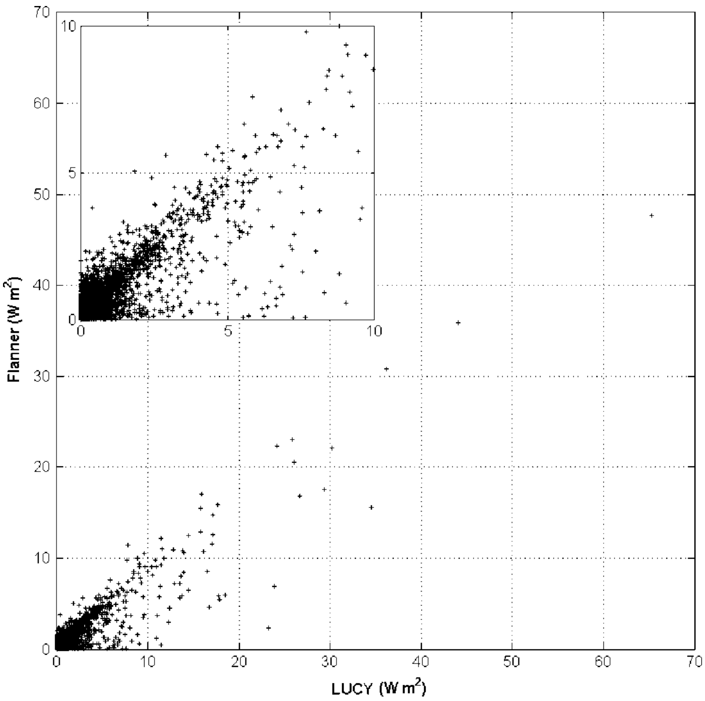

Figure 4. Pixel by pixel comparison at 0.5° × 0.5° between Flanner (2009) and LUCY for global urban areas ($N = 15,096$).

by pixel comparison is shown in Figure 4. There is a good agreement overall between the two models. However, occasional overestimations are made by LUCY (up to 21 W m^{-2}). By examining the spatial variations between the two models using difference map (Figure 5) it is evident that these occasional overestimations are found in areas close to large water bodies. This is an artefact produced when decreasing the pixel resolution of LUCY. The inset in Figure 5 shows an example of how this apparent overestimation occurs. A single large pixel could be located on the edge of land, leaving the major part of the pixel located in water, hence only a few data points are included in the aggregation calculation resulting in possible overestimation. Since a majority of urban areas are found at coastal locations, these areas have to be considered as important and should not be removed in the comparison between the two models. Flanner's (2009) global model did not include the contribution from vehicles or metabolism, so produces lower heat emissions than LUCY (Figure 4). The inclusion of those components meant that LUCY is also more sensitive to very low levels of anthropogenic heat.

From LUCY, the global average heat emissions in urban areas (CIESIN, 2004) range from 0.7 to about 3.6 W m^{-2} through the day, and are slightly greater on weekdays than weekends (Figure 6). This average peak of 3.6 W m^{-2} released into the atmosphere at global

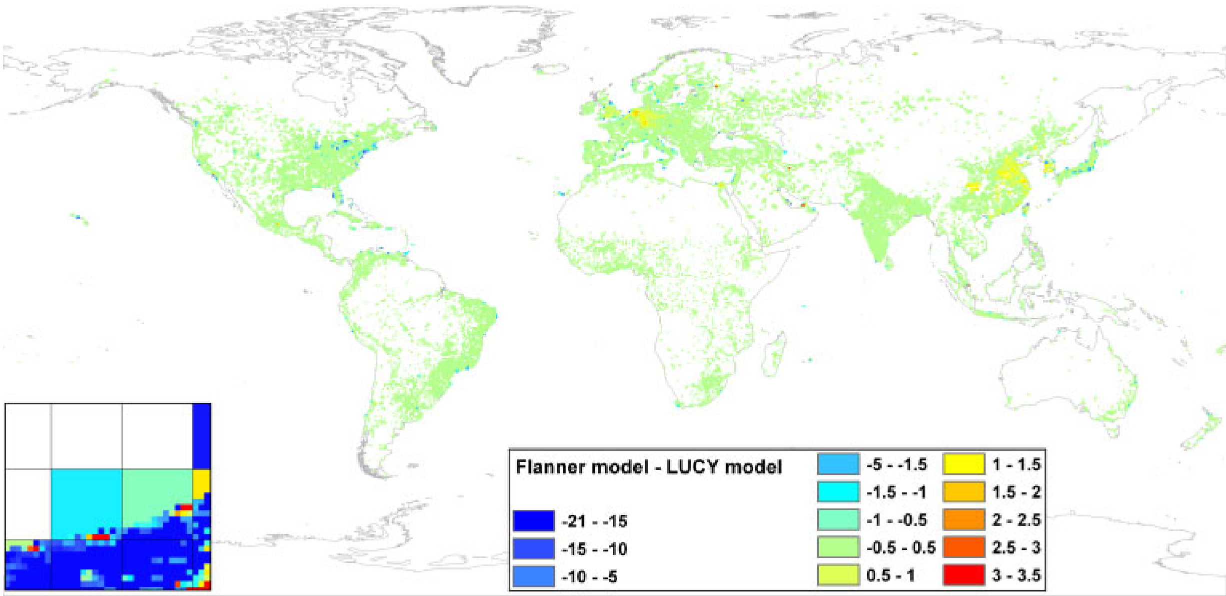

Figure 5. Difference in annual average Q_F (W m^{-2}) between the model presented by Flanner (2009) and LUCY (spatial resolution = 0.5°) for global urban areas. Inset: enlargement of the Belgian coastline illustrating the difference in spatial resolution between the two models. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

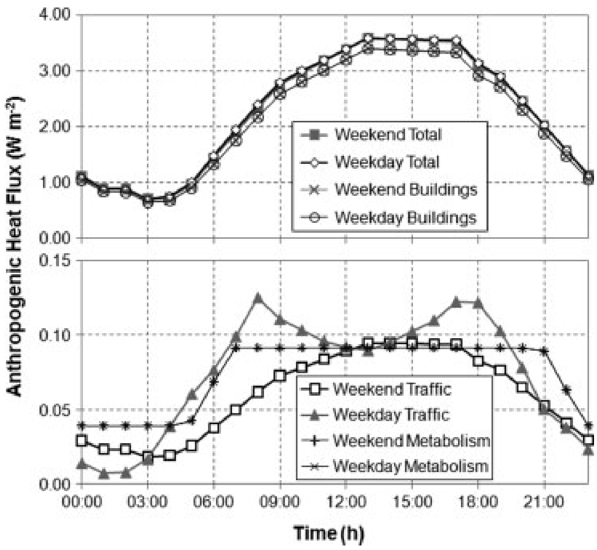

Figure 6. Global average daily anthropogenic heat emissions in urban areas.

scale by every urban area shows the impact of human activities on local climates. The maximum differences occur during morning and evening peak traffic hours. Q_B was the largest contributor (between 89 and 96%) to heat emissions globally. Thus the shape of the mean diurnal cycle in urban areas reflects the pattern of building emissions. Vehicle emissions altered the composition of Q_F a little, but the effect of morning and evening traffic peaks measured in many cities were not evident, despite others who estimated the contribution to Q_F to be over 25% (Lee *et al.*, 2009), 32% (Smith *et al.*, 2009) or even up to 62% in the summer (Sailor and Lu, 2004). This suggests Q_V maybe underestimated globally in LUCY. In Manchester around 50% of transport heat emissions were released from motorways surrounding and passing through the city – a factor which was not taken into account in LUCY. It would provide increased number of vehicles to raise the heat emissions from the Q_V component in many cities.

All the weekend days (Thursday–Sunday) possible where there were no public holidays are modelled to compare with a normal weekday. Saturdays and Sundays have the greatest impact on heat emissions (−0.6 to −0.73% and −0.57 to −0.66% respectively), but also vary depending on the time of year (not shown). Fridays and Thursdays had a much smaller effect, with Fridays generally affecting heat emissions more (−0.02% compared to −0.002%). The weekday diurnal cycles are compared for each month (Figure 7). Differences between months are greatest during the middle of the day, ranging up to 1 W m^{-2} at 1 pm. The months with the highest heat emissions are December, January and February. July and August produce heat at the higher end of the range, while the least anthropogenic heat is emitted in May. Regional climates had the greatest effect on heat emissions. Most anthropogenic heat was produced during the Northern Hemisphere winter months because the majority of urban areas are located in there. There are also relatively high heat emissions during the Northern Hemisphere summer months, because increased cooling energy demand is taken into account. May, the month with the lowest heat emissions, is probably because the outdoor temperatures across the world at that time are the closest to producing thermally comfortable temperatures inside buildings.

Work days in different countries have a distinct effect on total Q_F. Heat emissions on Fridays are less than on Thursdays because more countries set aside this day as a weekend (26 compared to six). The dominant weekend

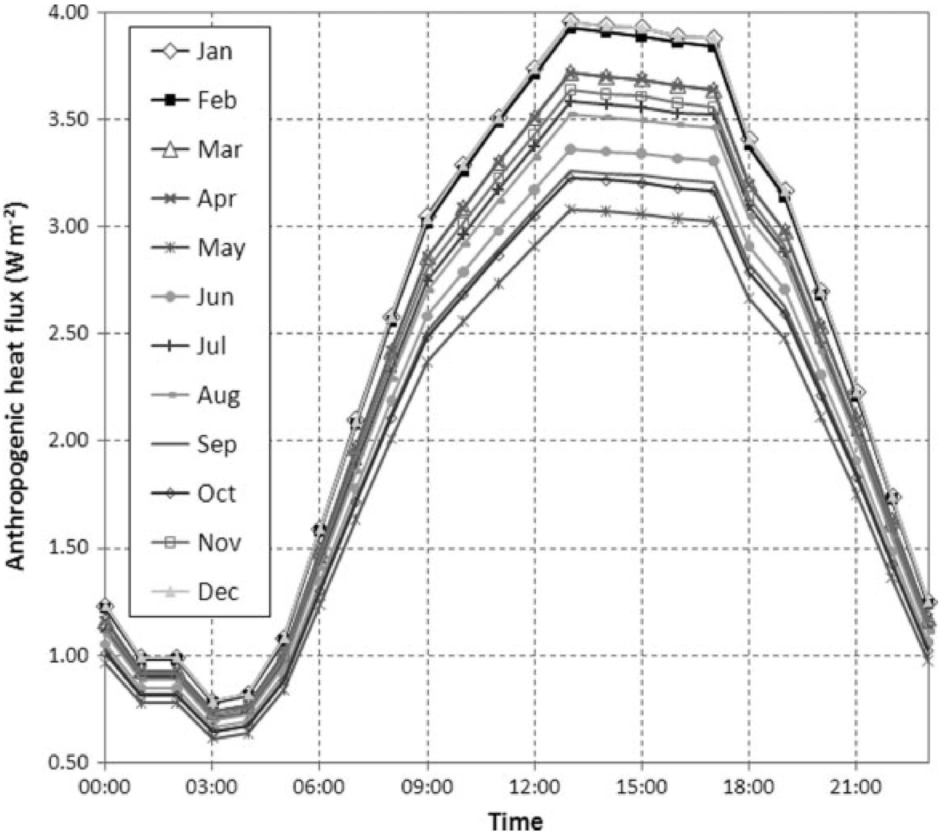

Figure 7. Average global weekday anthropogenic heat emissions by month.

pattern (Saturdays and Sundays) clearly led to a reduction in heat emissions in urban areas, even despite a possible underestimation of Q_V (which had a clear weekly pattern). This seems to be slightly more heat produced on Saturdays than Sundays, however these days are not modelled for every month so this may not be a conclusive difference. While the work week in countries usually does not change, Algeria's Thursday/Friday weekend was replaced by a Friday/Saturday weekend recently, in line with many other Arab countries (BBC News, 2009), so this would need to be altered in future versions.

Several days were chosen to illustrate the effect of public holidays on Q_F. Holidays observed widely across the world, such as Christmas Day (186 countries), May Day (157 countries), and Boxing Day (92 countries), were compared with holidays in single countries (USA Independence Day) and over large land areas (Victory Day observed in Russia and many former Soviet republics) (Figure 8). The largest reduction in heat emissions occurred when the public holiday fell on a weekday (Monday), producing a difference of 0.13% on Boxing Day. Less heat was emitted on May Day than Christmas Day, with the Independence Day holiday also having less heat release than Christmas. Heat reductions on Victory Day were about three times greater than Independence Day.

The sensitivity of LUCY to changes in the variables was examined by changing single variable over a one day simulation (Figure 9). May 16th was chosen because it was a weekday with no public holidays in any country.

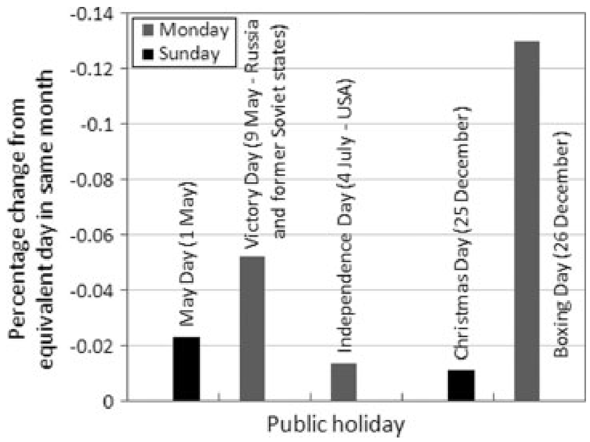

Figure 8. Effect of public holidays on global average anthropogenic heat in 2005.

Anthropogenic heat increases for each variable increase, and decreases when each variable is reduced. Population density had the greatest effect on the model, with a 10% change in heat emissions resulting from a 10% change of the variable. Energy consumption affected the emissions by more than 9% following a 10% change. The remaining five variables influenced anthropogenic heat by less than 1%. Average vehicle speed affected heat emissions slightly more than vehicle numbers. Considering the three vehicle types, changing the freight heat emission factor had the biggest effect and there was almost no change with motorcycle emissions.

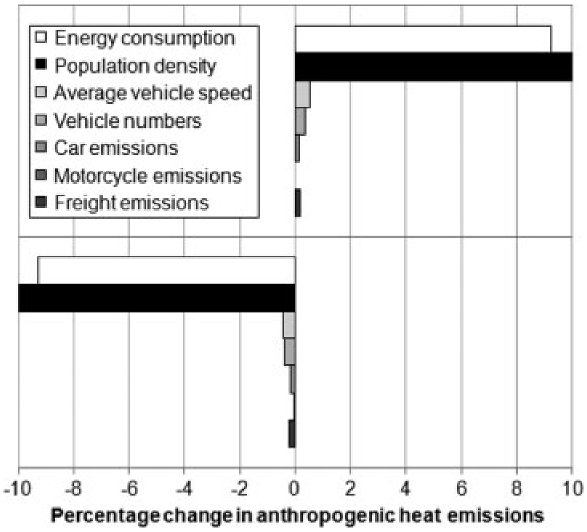

Figure 9. Sensitivity analysis of a +10% and −10% change to the variables in LUCY.

While the temperature which is perceived to be comfortable is not thought to vary over time with climate change (Amato *et al*., 2005), it does increase with increased outdoor temperatures (Nicol and Humphreys, 2002). This suggests that there may be a wider range of monthly outdoor temperatures (enlarged at the upper end of the scale) where less energy is needed for cooling than estimated in LUCY. This would reduce the sensitivity of the model to changes in energy consumption linked to temperature (Figure 9). Population density is extremely important for determining heat emissions in urban areas because it can be interpreted as a measure of building density, which is thought to intensify the UHI effect from anthropogenic heat as well as the absorption of solar radiation (Roth, 2007), so the model should be sensitive to this component.

5. Anthropogenic heat flux in individual urban areas: London and Tokyo

LUCYcity was used to simulate anthropogenic heat for London and Tokyo. These are examined in more detail because previous studies have calculated heat emissions. One week was modelled for each month.

The weekday and weekend average is calculated for each month (Figure 10a). During the winter months (December–January) the mean heat emissions is 24 W m^{-2} across Greater London. This drops to around 16 W m^{-2} in May, June and September, with a slight increase in July and August to 17 W m^{-2}. The spatial and temporal variations during a weekday in one of the coldest months (February) are illustrated in Figure 11. The central areas of London were clearly defined even in the night hours, with an increase in anthropogenic heat from 6 am. Peak emissions reached over 100 W m^{-2} from midday to 3 pm, remaining high at 6 pm before declining in the evening. These results can be compared with the more detailed representation of building heat emissions in London by Hamilton *et al*. (2009). In their model the areas which produced the most heat were in the very centre, with some high points in the south and west. Although there was clearly a loss of detail in LUCYcity, the patterns in both broadly match. Hamilton *et al*. (2009) state that vehicle heat emissions in London averaged 2 W m^{-2} annually, in contrast to LUCYcity with an average of 0.43 W m^{-2}. Q_V should have been closer to the 2 W m^{-2} estimate, because the vehicle emissions factors were based on the UK fleet which probably underestimates traffic intensity and average vehicle speed in the Greater London area. While emissions from vehicles are lower at high speeds (Smith *et al*., 2009), the number of vehicles on motorways (up to five times that on major roads in Toulouse) can outweigh this difference (Pigeon *et al*., 2007). There was a greater contribution to Q_F from metabolic heat (0.55 W m^{-2}).

Heat emissions in Tokyo are about three times greater than for London (Figure 10). The highest average heat flux of 70 W m^{-2} was in January. The summer months had a strong influence on anthropogenic heat, reaching a peak in August close to that in the winter. In contrast, winter heat emissions are modelled at almost double the summer anthropogenic flux by Ichinose *et al*. (1999). November had the lowest average heat emissions from LUCYcity (47 W m^{-2}). Saitoh *et al*. (2005) estimated a lower heat production in Tokyo, combining electricity, gas and petrol consumption to create an average of 28 W m^{-2} slightly lower than Ichinose *et al*.'s (1999) (1 km^2) value of 31 W m^{-2}. Like London, fine-scale (1 km^2) resolution grids of heat flux can be compared. Emissions reached a peak of 400 W m^{-2} in the centre during a winter day, while overall heat was greatly reduced by 9 pm. Low values were modelled in the central area occupied by the Tokyo Imperial Palace and surrounding gardens. The effect of this site (at 35.7 °N, 139.75 °E) on heat emissions was also identified in LUCYcity (Figure 11). The diurnal pattern of anthropogenic heat is similar to that modelled by Ichinose *et al*. (1999), reaching a peak at around 3 pm with the lowest values at 3 am. The highest estimated heat emission is 178 W m^{-2}.

Heat production in both Tokyo and London is greatest in the coldest winter months (Figure 10), which is due to the heating requirements for buildings (the dominant component of Q_F in both cities). Anthropogenic heat emissions in Tokyo were almost as high in the hottest months as the coldest months, whereas Ichinose *et al*. (1999) estimated that the winter heat flux was twice as much as in summer. However, their results used data from the late 1980s and summer air-conditioning in some sectors did not become widespread in Tokyo until later so the current results are likely to be more appropriate. This suggests that time period is important because of changing behaviours and technology. It should be noted in the current version that the balance points are fixed so do not pick up the impact of different behaviours and building codes regionally.

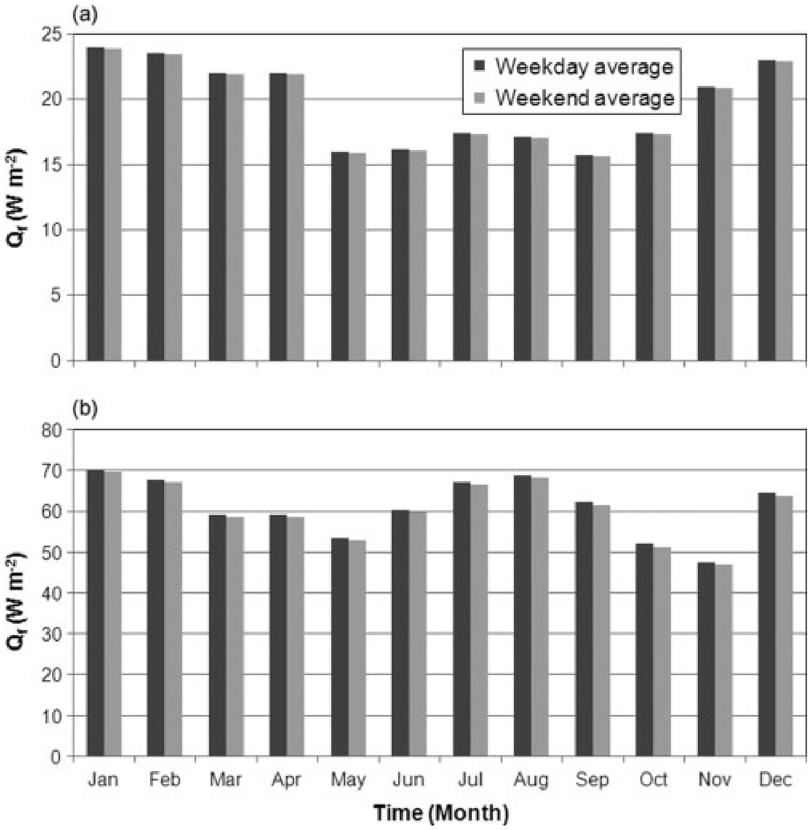

Figure 10. Monthly average anthropogenic heat emissions in (a) London and (b) Tokyo during 2005.

The extreme values estimated in Tokyo and London are lower than those modelled by Ichinose *et al.* (1999) and Hamilton *et al.* (2009) because LUCYcity has a much lower spatial resolution. As resolution increases, more detailed estimates can be made from bottom-up methods, as shown by Heiple and Sailor (2008) in Houston. In both the spatial variation within the cities is evident (Figure 11), with population density proving a reasonable proxy for estimating where the highest emissions were in comparison to the fine-scale models.

6. Comparison of anthropogenic heat in urban areas across latitudes

Anthropogenic heat emissions for a number of urban areas across the world are compared with other studies. Two weeks were modelled for each city, one in February and the other in August so that heat production during the warmest and coldest months in both hemispheres could be estimated. The averages for London and Tokyo are calculated using the 12 weeks already modelled (Section 5) where spatial variation was clearly visible.

The urban area which produces the highest average heat emissions is Tokyo (60.8 W m^{-2}), about twice that estimated by Flanner (2009) but less than was modelled by Ichinose *et al.* (1999) (Figure 12). These results are as expected given the difference in areal extent over which each estimates are based. New York, Paris, San Francisco, Shanghai, London and Vancouver have the next highest averages. The remaining cities had averages lower than 9 W m^{-2}. These are larger than the Flanner (2009) average for all cities, apart from Ouagadougou, Lagos and Kinshasa, where no emissions were estimated. London has a greater average heat flux than estimated by Hamilton *et al.* (2009), while New York had a lower average than suggested by Oke (1987), although the LUCYcity results are for a larger area but more recent so there will have been changes in energy consumption. Manchester and San Francisco had very similar averages compared to other models of heat emissions.

The highest individual grid cell heat fluxes in urban areas were located in New York (577 W m^{-2}), Paris (261.5 W m^{-2}), Tokyo (178 W m^{-2}), San Francisco (173.6 W m^{-2}), Vancouver (119 W m^{-2}) and London (106.7 W m^{-2}). The maximum values for all cities were much greater than those modelled by Flanner (2009). Ouagadougou and Kinshasa had the lowest modelled maximum heat fluxes (less than 3 W m^{-2}). Maximum heat emissions estimated at Ouagadougou, Lagos and Rio de Janeiro were all relatively close to the values produced by others. Cities at the lowest latitudes generally produced much less heat than at the higher latitudes, although there were fewer heat emissions in Helsinki and Toulouse than might be expected.

Q_B was the largest component of Q_F in cities in more developed countries (92% or more), with Q_M and Q_V very similar to each other. In Ouagadougou, Lagos and Kinshasa the Q_M component was much more important – between 30 and 71.5% of the total. Rio de Janeiro and Shanghai also had higher Q_M percentages than the

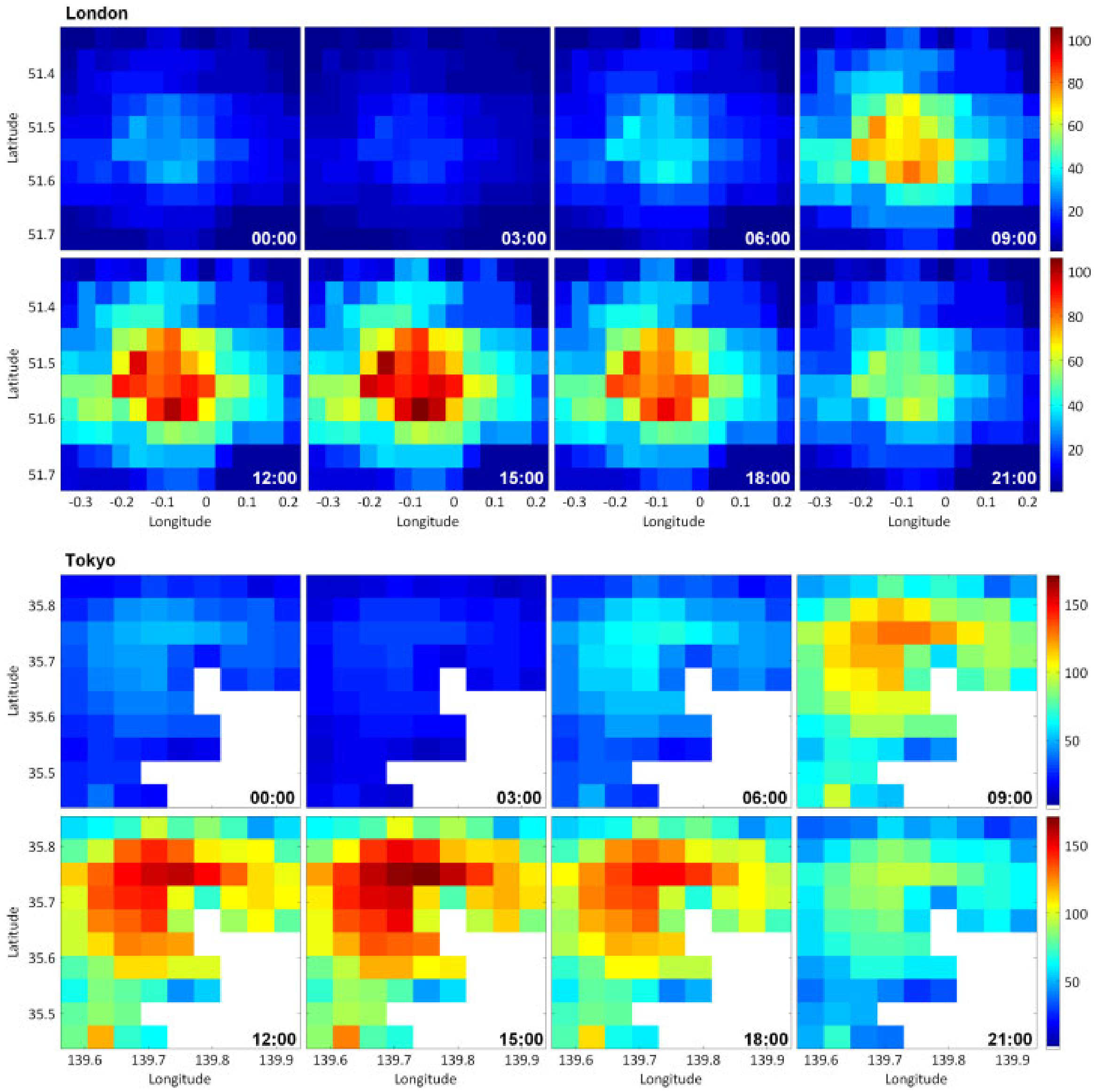

Figure 11. Diurnal patterns of the anthropogenic heat flux (W m^{-2}) in London and Tokyo on Monday 14 February 2005. This figure is available in colour online at wileyonlinelibrary.com/journal/joc

other cities (around 7%). Despite the different population densities, population count and anthropogenic heat emissions, the two French and British cities had very similar compositions compared to each other. This also occurred to a certain extent in the USA cities.

The advantage of LUCYcity is that the anthropogenic emissions in any urban area or region can be examined, once it is located in the global grid, and that changes can be made to the base grids to make the estimates more accurate. Less research has been carried out on UHIs in (sub)tropical regions than in mid-latitude areas (Roth, 2007), but this model allowed initial investigations of cities in these regions.

New York was one of the few cities identified in Flanner (2009) because it produced the highest anthropogenic heat values; this was matched by LUCYcity which also estimated the largest heat emissions occurring in New York (Figure 12). The maximum values in urban areas may be greater than in reality, because a certain amount of heat can be transported out of cities through the sewers, either from surface warmth being absorbed by rainwater (Offerle *et al*., 2005) or hot water and other waste being removed via the system (Ichinose *et al*., 1999).

Wienert and Kuttler (2005) found that only 6% of variation in UHI intensity was accounted for by latitudinal changes, mostly attributed to solar radiation and anthropogenic heat. This is in agreement with the decision to use average temperatures to scale energy use rather than latitude, unlike Flanner (2009) who used the amount of solar radiation to determine how much energy is used for heating and cooling. The latitude of each city modelled did not clearly affect anthropogenic heat; the smallest maximum Q_F was estimated in the cities near the equator this was more likely a consequence of low energy consumption. Air-conditioning use may also have been overestimated in countries which cannot afford widespread

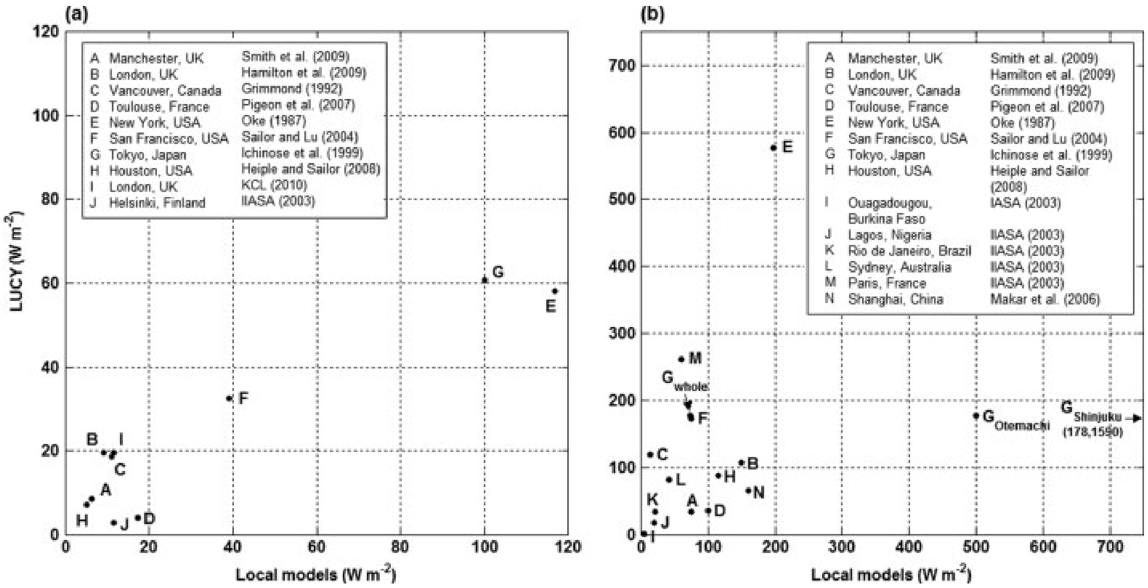

Figure 12. Comparison between LUCY and earlier studies of anthropogenic heat emissions for different cities around the world: (a) mean Q_F and (b) maximum Q_F. In (b) for Tokyo [G] three areas at three scales are shown (Shinjuku 250 m^2; Otemachi 1 km^2 and whole of Tokyo 621 km^2).

building cooling. Some models have used set-point temperatures inside buildings (when air-conditioning units turn on) ranging from 22 to 27 °C (Zhu *et al*., 2007), which would reduce the Q_B component.

The composition of Q_F is similar in cities within the same countries as the same vehicle number and energy consumption data are used. The contribution of metabolic heat to total Q_F in cities in the USA was less than 5%, as suggested by Sailor and Lu (2004), but in countries such as Burkina Faso, DR Congo and Nigeria it was illustrated how lower energy consumption increased the importance of Q_M (Sailor and Lu, 2004). This strengthens the argument that metabolic heat should be included in local and global studies of anthropogenic heat in urban areas. Q_M may also be affected by tourism, which is an important part of the economy of many cities. While some people may stay in hotels within the urban limits, many others not accounted for in the model, will travel into the city during the day. Tourist numbers also fluctuate depending on the time of year.

Much of LUCY is based upon population density figures, which reflects where people reside rather than work. Domestic and non-domestic energy consumption patterns are different (e.g. Ichinose *et al*., 1999; Dhakal *et al*., 2003, 2004; Hamilton *et al*., 2009), so in future versions business districts within a city could be located and separate cycles applied. Diurnal cycles can differ between summer and winter, as noted by Sailor and Lu (2004) where morning and evening energy peaks occurred only in the winter when lighting was required, or between countries due to economic reasons, such as the higher energy use recorded in Toulouse in the evening when it was cheaper (Pigeon *et al*., 2007).

7. Conclusions

A global model of heat emissions has been created which for the first time contains all the components of anthropogenic heat flux. Other models of anthropogenic heat have been restricted to small areas, or omitted some of the components despite modelling global heat production. As part of the model, a database of underlying facts and assumptions was assembled. These take into account different working patterns and public holidays in every country, which have not been included in this type of model before, vehicle use and energy consumption in different countries.

The results of the simulations show that anthropogenic heat varied widely throughout the year, throughout the day, between countries and urban areas. An assessment of the heat emissions estimated with LUCY reveal they were reasonably close to those produced by a global model (Flanner, 2009) and a number of city models, so results from LUCY can be used with a degree of confidence. Urban and rural areas throughout the world can be examined using LUCY, which outputs statistics about the average heat emissions, maximum and minimum values and variation within a city. Heat emissions estimated by LUCY show the spatial variation and range of a bottom-up model, using top-down methods. The deviation between urban areas was the result of changes in latitude to a certain extent, but it was found that the characteristics of each city, such as population density and the amount of energy consumed (scaled according to the monthly temperature), were more important.

The most evident improvement to the model includes the vehicle heat component which may be underestimated due to the type of data used. Traffic count data would be more accurate but the availability is limited. Building heat emissions could be improved by studying the link between temperature and the amount of energy required to heat/cool buildings to a satisfactory temperature dependent on the time of year.

One of the main advantages of this model is that it can be scaled from global to city level, and the background databases can be edited to include specific diurnal and seasonal vehicle and energy consumption patterns, local holidays and even flows of people within a city. If better information about individual cities can be built up within this database, then the accuracy of this model can only improve, allowing it to be included in global climate models in the future.

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