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Impact of city changes and weather on anthropogenic heat flux in Europe 1995–2015

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ABSTRACT

How people live, work, move from place to place, consume and the technologies they use all affect heat emissions in a city which influences urban weather and climate. Here we document changes to a global anthropogenic heat flux (Q_F) model to enhance its spatial ($30'' \times 30''$ to $0.5° \times 0.5°$) resolution and temporal coverage (historical, current and future). Q_F is estimated across Europe (1995–2015), considering changes in temperature, population and energy use. While on average Q_F is small (of the order 1.9–4.6 W m^{-2} across all the urban areas of Europe), significant spatial variability is documented (maximum 185 W m^{-2}). Changes in energy consumption due to changes in climate are predicted to cause a 13% (11%) increase in Q_F on summer (winter) weekdays. The largest impact results from changes in temperature conditions which influences building energy use; for winter, with the coldest February on record, the mean flux for urban areas of Europe is 4.56 W m^{-2} and for summer (warmest July on record) is 2.23 W m^{-2}. Detailed results from London highlight the spatial resolution used to model the Q_F is critical and must be appropriate for the application at hand, whether scientific understanding or decision making.

1. Introduction

The climate of a city depends not only on its size, location and synoptic setting, but also the socio-economic, cultural, and political characteristics of the urban area. How people live, work, move from

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place to place, what they consume and the technology they use all affect the fabric, morphology and emissions in a city. These in turn all affect its climate. The focus in this paper is heat emissions from human activities in cities – the anthropogenic heat flux (Q_F). This is released by mobile sources (e.g., related to transportation), fixed sources (e.g., heating, cooling, lighting) and by people themselves (i.e., metabolism). It can be transferred within the urban system via sensible heat, latent heat (phase change) and waste water. The sources and timing of anthropogenic heat vary significantly with city location and characteristics (Flanner, 2009; Allen et al., 2011; Sailor, 2011; Iamarino et al., 2012). Spatial differences exist both across a city (for example, between residential, industrial and commercial land uses) and between cities (because of patterns of energy consumption related to climate or socio-economic development). In addition, cities and the behaviour of their residents change through time. In the last century, for example, significant changes in the use of lighting, heating and personal vehicles, use of appliances (e.g., computers and mobile phones), and summertime air conditioning all have altered anthropogenic heat emissions in cities around the world. To model the climate of cities and the effects of cities globally, understanding of anthropogenic heat fluxes at different spatial and temporal scales is needed (Oleson et al., 2011; McCarthy et al., 2012; Zhang et al., 2013).

The **L**arge scale **U**rban **C**onsumption of energ**Y** model (LUCY) is a tool to simulate the anthropogenic heat flux both spatially and temporally (Allen et al., 2011). In this paper, we describe the recent developments to LUCY (specifically, the addition of new temperature functions as predictors of energy use, a dynamic spatial averaging utility, a new graphical user interface to enhance ease of use, and options to upload new data) and use LUCY to assess changes in anthropogenic heat flux over a 20 year period (1995–2015) across Europe. We demonstrate that the spatial resolution used to model the anthropogenic heat flux is critical and highlight implications for scientific understanding and decision making.

2. Large scale urban consumption of energy model (LUCY) model

The **L**arge scale **U**rban **C**onsumption of energ**Y** model (LUCY) calculates the sensible heat components of anthropogenic heat flux (Allen et al., 2011). The version used here has been developed further and can now run at variable spatial scales (Section 2.1) and for longer temporal duration (Section 2.3), with enhancements also in the temperature response (see Section 2.2). In addition, new graphical user (Section 2.3) and data interfaces have been developed to enhance ease of use (see Appendix A).

2.1 Spatial resolution

The magnitude and spatial variability of the anthropogenic heat flux is dependent on the resolution at which the calculations are performed. The latter is usually dictated by the input data used. LUCY employs numerous global datasets originating from various sources (Allen et al., 2011): population density, air temperature, energy consumption and traffic data (numbers of cars, freight vehicles and motorbikes). Ideally these data would be available for each day (e.g., temperature) or year (e.g., population density) at the basic spatial unit. However, some are only available at country level and most national statistics are not updated annually worldwide.

A key dataset used is the population density. Previously, the Gridded World Population (GWP, v3; CIESIN, 2005), which has a $2.5' \times 2.5'$ resolution, was used as the basis for calculations (Allen et al., 2011). In LUCY v2013a the Global Rural–Urban Mapping Project (GRUMP, v1; CIESIN, 2011) dataset is used, though the ability to select the GWP dataset has been retained as an option. To make use of the higher spatial resolution of GRUMP, LUCY has been modified to have a finer resolution of 30 arc-seconds (about 1 km^2 at the equator). Both population datasets are constructed from national or subnational input units (usually administrative units) of varying resolutions. Beyond its spatial resolution, the GRUMP dataset differs from GWP in that it is slightly modified based on night-time lights, i.e., using algorithms to redistribute population into dense urban areas (CIESIN, 2011). If the application demands unmodified census population data that are rendered in gridded format, then GPW is preferred. For a more detailed comparison, see CIESIN (2011). The GRUMP data are estimated for 1990, 1995 and 2000, whereas the GWP data also include predicted estimates for 2005, 2010 and 2015 (CIESIN, 2005).

Introducing the ability to use the GRUMP dataset within LUCY results in a considerable increase in the database size due to the finer spatial resolution. To facilitate its use, the dataset is divided into $5° \times 5°$ tiles and can be run at 30″, 1′, 2.5′, 5′, 10′, 20′ and 0.5° resolution. Thus, the areas modelled can be selected from the minimum spatial resolution, through to a city, a region or the globe (latitudinal range of 82°N to 58°S) (the WGS84 datum is used).

2.2 Temperature response

Temperature is a key control on energy use within buildings; a trigger for increased use of heating in winter or air conditioning in summer. This building energy use, which is a significant portion of the total energy use (Eiker, 2009), results in heat release externally in the urban environment. The internal temperature of a building is considered thermally comfortable at a threshold termed the temperature balance point ($T_{F_{BP}}$); deviation from the balance point results in increased energy used for either heating or cooling. Nicol and Humphreys (2002) found this temperature balance point to be equivalent to a monthly average air temperature of 12 °C, a value found to be valid in different regional climates (Humphreys, 1976).

The amount of energy used, however, depends on local factors. In LUCY (v2013a) heating degree days (HDD) and cooling degree days (CDD) are used in relation to national income (i) which changes with time (t, years). For each year HDD and CDD are calculated relative to 12 °C using the Willmott et al. (2009) $0.5° \times 0.5°$ terrestrial gridded monthly temperature dataset (available for 1901–2008). The combined total annual HDD and CDD (HDD + CDD) are determined for each country for each year.

For each country the annual energy consumption (IEA, 2011) per capita (CIESIN, 2005) is compared to the total HDD + CDD. Energy consumption of a country relative to the respective annual HDD + CDD generally increases with its income. Here the World Bank (2012) classification is used to classify countries into four income groups (Fig. 1).

With actual monthly mean air temperatures and monthly energy consumption data, it is possible to estimate the change in the temperature scaling factor F_{TS} relative to HDD and CDD (termed here response functions I_{HDD} and I_{CDD}). Fig. 2 shows the normalized monthly energy consumption for 1995–2008 as a function of temperature expressed as monthly total HDD. The monthly energy (E) is normalized relative to the minimum (E_{min}) and maximum (E_{max}) energy consumption within the time period examined. The three countries (subscript j) shown in Fig. 2 are classified as high income countries by the World Bank (2012). The slope is the response function for HDD ($I_{HDD(j,t)}$).

Using the four national income classes (World Bank 2012; index i), different $I_{HDD(i,t)}$ and $I_{CDD(i,t)}$ are retrieved (Fig. 3). Thus, each grid cell (x,y) in a country with national income type (i, for year t) will have a $F_{TS_{x,y}}$ value that is dependent on the monthly HDD or CDD (one term will always be zero) and the corresponding response function $I_{HDD(i,t)}$ or $I_{CDD(i,t)}$:

$$F_{TS_{x,y}} = T_{F_{BP(i,t)}} + [\mathrm{HDD}_{x,y}\ I_{HDD(i,t)}] + [\mathrm{CDD}_{x,y}\ I_{CDD(i,t)}] \qquad (1)$$

As LUCY is a global model, it covers areas that experience extreme temperatures (e.g., northern Canada and inner Siberia) where the relation of energy used and total HDD cannot be considered linear anymore beyond a monthly HDD of 600 °C. In these cases, the response function ($I_{HDD(i,t)}$) is adapted to the following relation:

$$I_{HDD(i,t)} = [3 \cdot 10^{-10}\ \mathrm{HDD}^2_{x,y}] - [1 \cdot 10^{-6}\ \mathrm{HDD}_{x,y}] + 2.9 \cdot 10^{-3} \qquad (2)$$

This is independent of national income grouping. The annual average F_{TS} globally should be close to 1. The mean global F_{TS} for 1961–90 is calculated to have a 2% over-estimation, which for the application here is considered to be acceptable.

To improve the performance of the model, monthly total energy consumption statistics by country/economic status should be used to specify $I_{HDD(i,t)}$ and $I_{CDD(i,t)}$. Such data are more difficult to obtain than annual data. As more data on monthly energy consumption are analysed, more robust relations between energy used and temperature will be possible for the different national income classes and for each country.

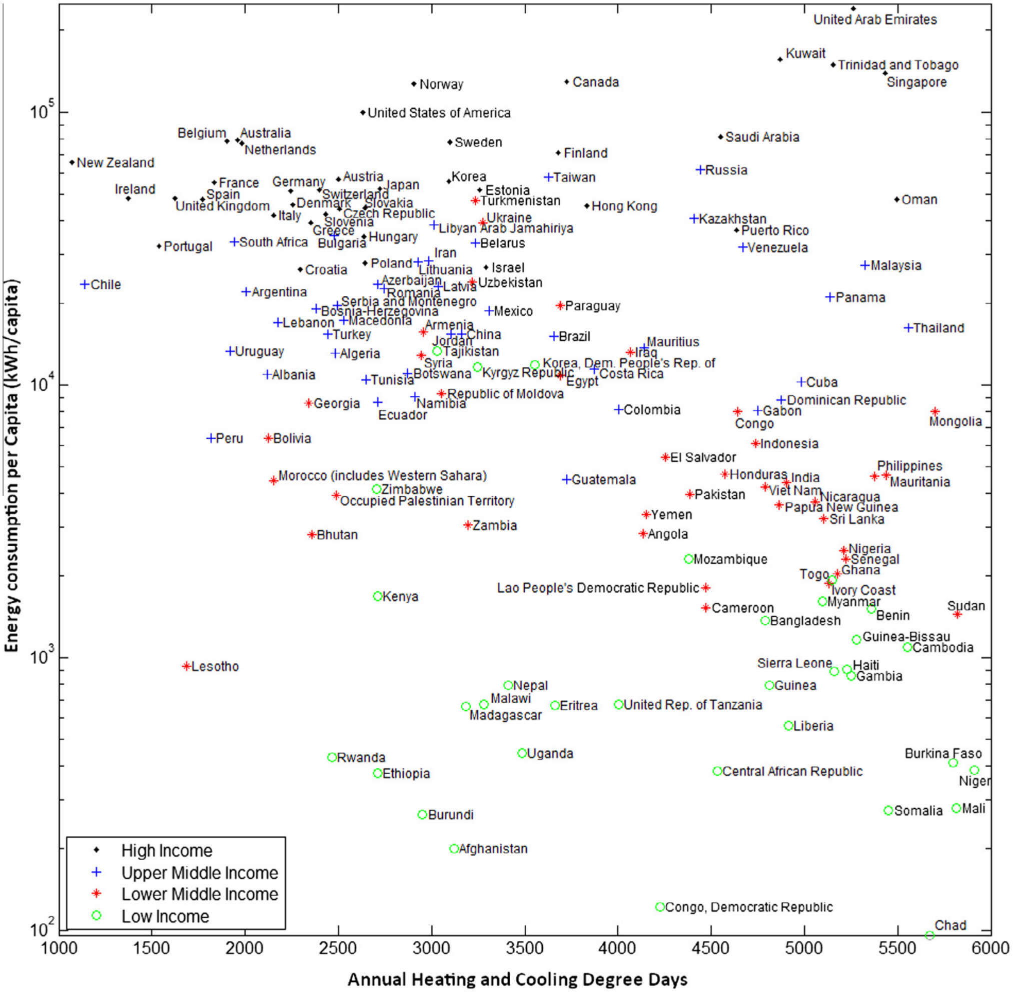

Figure 1. Annual energy consumption per capita versus combined total of annual heating and cooling degree days (°C) for countries with a population greater than 1 million for 2005.

Examining the inter-annual pattern of energy consumption in relation to the Willmott et al. (2009) monthly mean temperature dataset for the UK and the US, it is evident that the two countries show different patterns (Fig, 4). The US has both a summer and winter peak in energy consumption, whereas the UK only has a winter peak. As not all countries use energy extensively to cool their buildings in summer, F_{TS} should not always increase when CDD increases. This is especially evident for mid and northern Europe (e.g., Sweden). Therefore, for each country and year in the model it is now specified if building air conditioning occurs widely or not. This can be changed by the user.

Examining changes in normalized energy consumption compared to total monthly CDD and HDD for two different time periods for the US, changes through time (i.e., related to technological adoption) are evident (Fig. 5). The level of energy used for heating shows a similar response but cooling only becomes evident at the national scale during the later period (1995–2005). Similarly, Europe is also increasing its air conditioning use (Euroheat and Power, 2006, p8).

Using long term monthly average temperatures LUCY is not responsive to actual conditions (e.g., warm or cold days). Therefore the new version of the model has been adapted to allow actual daily temperature to be used (LUCY v2013a) to provide a more dynamic and appropriate response to heat

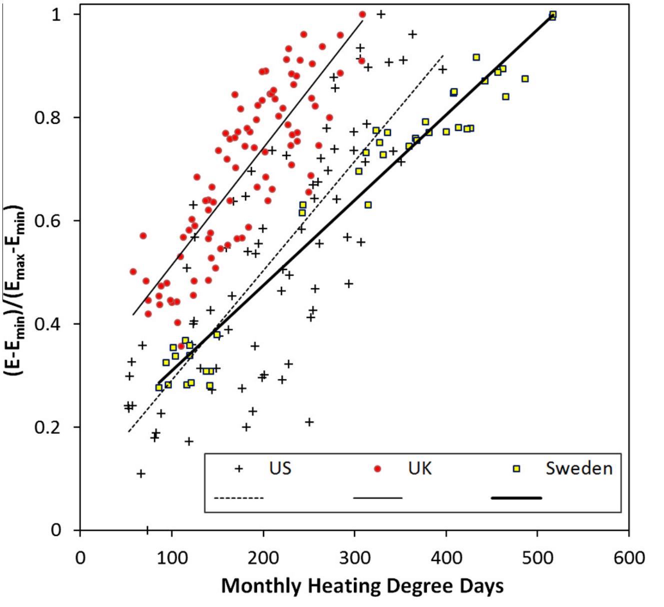

Figure 2. Normalized monthly energy consumption versus monthly heating degree days (°C) for Sweden (data source: SCB, 2012), the UK (data source: DECC 2012) and the US (data source: EIA, 2012a) for the period 1995–2008.

waves or extremely cold periods, which are typically considerably shorter than a month. Each daily temperature is converted to a monthly value of HDD or CDD by assuming the specific daily value occurred for each day of the month, to allow Eqs. (1) and (2) to be used.

2.3 Model deployment

The model operates at hourly temporal resolution for periods of a day to years (as currently specified it can run between 1900 and 2100). To allow a user to check the data available, a graphical user interface (GUI) is now provided. The programme uses the efficient matrix processing of MATLAB (current version R2012b) and the MATLAB Compiler Runtime (MCR) to provide full functionality without the need to have a full version of MATLAB installed.

Through the GUI a user can change most model input parameters, such as time period and region of interest, as well as input data such as global grids of daily temperature patterns etc. The data summary window indicates the sources available (see Appendix A) for the specified period of interest. If no data

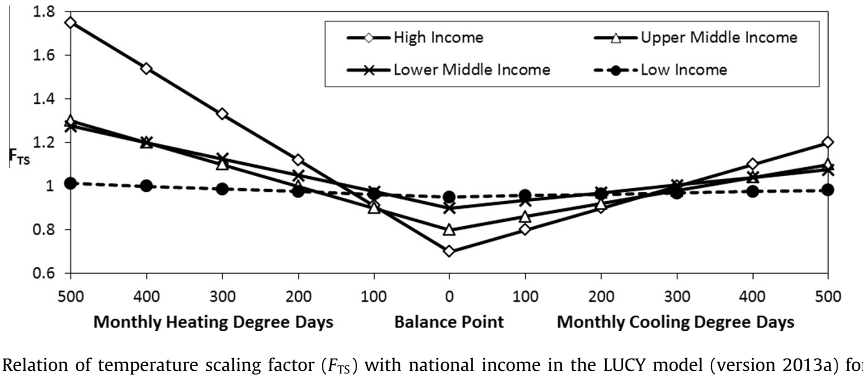

Figure 3. Relation of temperature scaling factor (F_{TS}) with national income in the LUCY model (version 2013a) for 1995 to present. See text for further explanation.

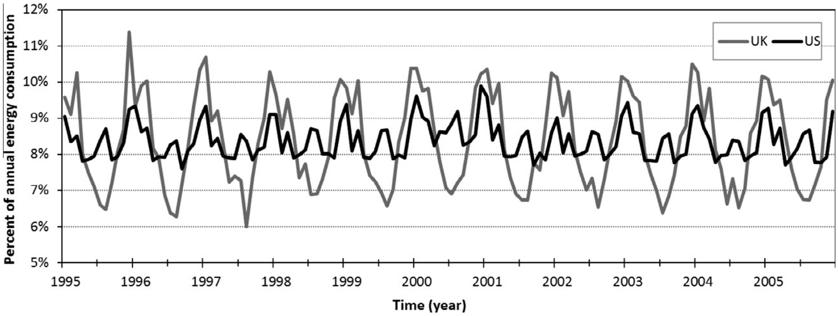

Figure 4. Monthly energy consumption as a percentage of the annual consumption for the UK and the US for 1995–2006.

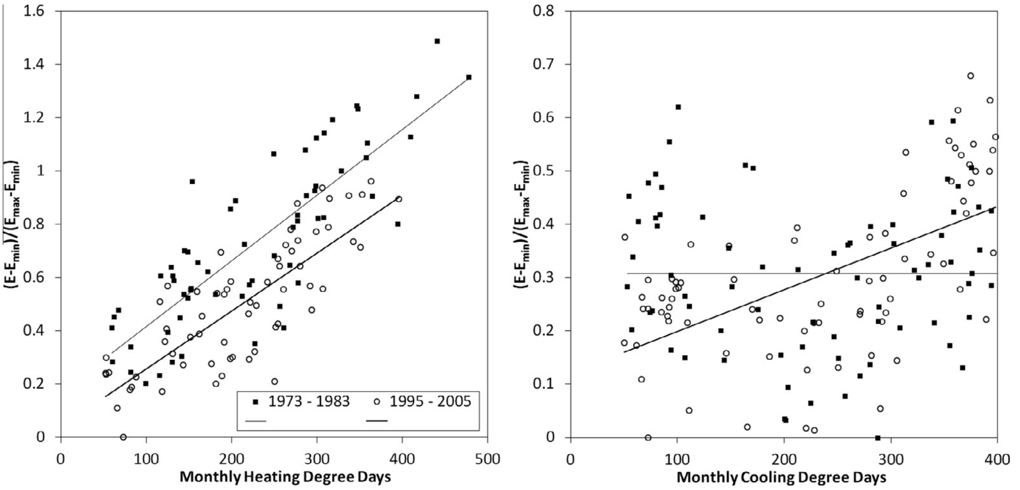

Figure 5. Normalized monthly energy consumption versus (left) heating degree days (°C) and (right) cooling degree days (°C) in the US for two periods (1973–1983; 1995–2005). Note the difference in scales between the two graphs.

are available (e.g., number of cars), *NaN* (Not a Number) appears in the data summary table and the country will be excluded from the calculations. This only occurs for a very few small countries (e.g., San Marino) so is negligible on a global basis and can be resolved if data are available (see Appendix A). For population, energy and traffic, data for the year specified or the closest available to that requested are used.

The temperature datasets are not distributed with the base release of LUCY, but the LUCY format compatible annual files can be downloaded from the website (http://londonclimate.info/, Appendix A). The processing of these data includes the use of a mean filter at coastal locations to redistribute temperature values across the terrestrial grid points at the desired spatial resolution (see Section 2.1). If the specific year of interest is absent from the data folder when LUCY is performing calculations, the mean monthly temperatures for the period 1970–2000 (Willmott et al., 1998) are used.

3. Spatial averaging

The magnitude of the anthropogenic heat flux is highly dependent on the spatial scale at which it is estimated. In cities, peak values are associated with large buildings and busy roads. For example, Ichinose et al. (1999) cite a value of the anthropogenic heat flux greater than 1550 W m^{-2} for a small

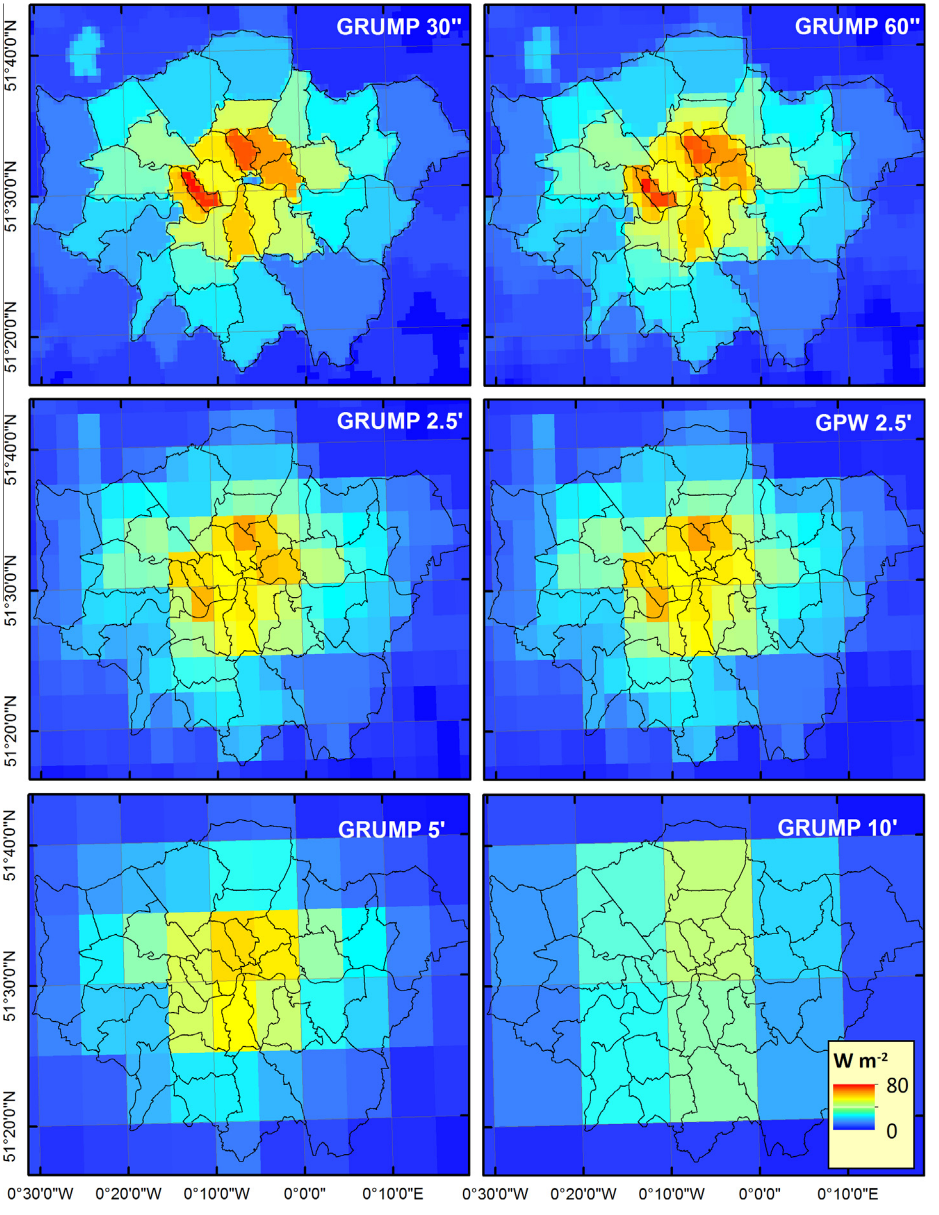

Figure 6. Annual average Q_F for 2000 at five different spatial resolutions (30″–10′) for London using the Global Rural–Urban Mapping Project (GRUMP) population density dataset (CIESIN, 2011). Annual average Q_F using the Gridded Population of the World (GPW) is also included (CIESIN, 2005). The black lines are borders of the 33 boroughs within the Greater London Authority. Projection: The British National Grid.

area (250 m^2) in Tokyo. This is three orders of magnitude larger than the values discussed here for urbanized Europe (see Section 4), which of course have been calculated at a much coarser scale. High resolution databases (100 m) typically are available for individual cities or small areas within them (Grimmond, 1992; Klysik, 1996; Ichinose et al., 1999; Pigeon et al., 2007; Quah and Roth, 2011). At the other extreme are the global models of Flanner (2009) (0.5° × 0.5°) and Allen et al. (2011) (2.5′ × 2.5′). Here we investigate the relation of the anthropogenic heat flux to the size of the area

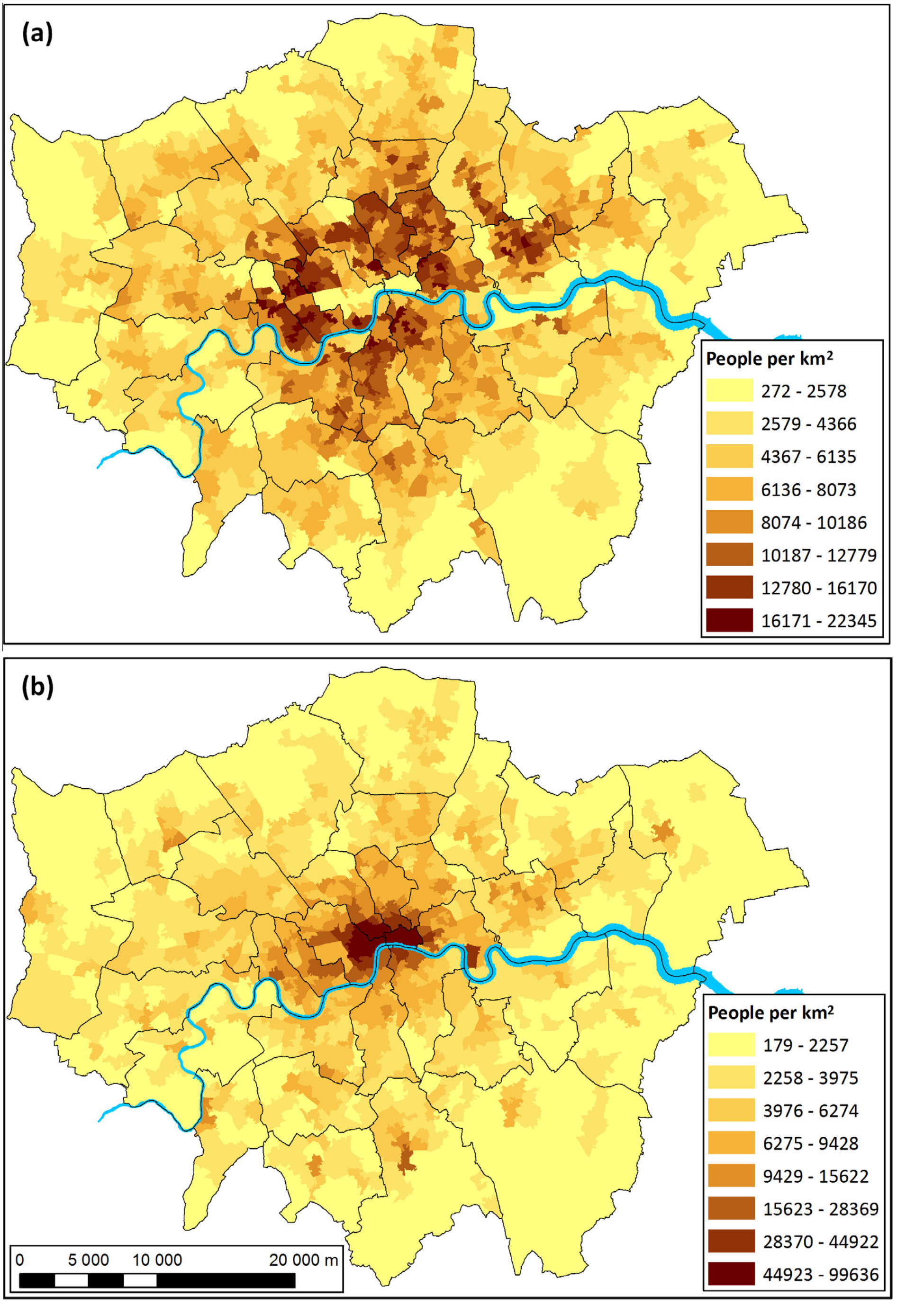

Figure 7. Population density for Greater London 2001 in (a) residents (people km^{-2}) and (b) daily working population (people km^{-2}) at MLSOA. See text for data sources. Natural breaks in ArcMap™ are used to select class breaks that best group similar values and maximize the differences between classes. Note these are different between maps. The black lines are borders of the 33 boroughs within the Greater London Authority. Projection: The British National Grid.

at which it is calculated to provide further insight into how the flux varies at different spatial resolutions. This work focuses on Greater London (GL), UK. We make use of the new capability to change spatial resolution within LUCY (v2013a) (as presented in Section 2.1).

Fig. 6 shows the spatial variation in annual average Q_F in London for the year 2000 at various spatial scales using the GRUMP dataset (Section 2.1). Patterns are primarily related to population density. There is also a clear decreasing trend in maximum Q_F as coarser spatial resolution is used, which is a direct result of the spatial averaging performed. Included in Fig. 6 is the GPW dataset (2.5′). As the GRUMP and GPW originate from the same basic data sources very similar values of Q_F are determined. For Greater London, the base source of population data is clearly related to census data at borough level (boundaries shown in Fig. 6). Calculating Q_F at a very high resolution (e.g., 30″), the census data are coarser than the actual LUCY spatial resolution used. Results show that census data can cause an underestimation of Q_F in certain areas, especially in the Central Business Districts (CBD). Furthermore, given census data are related to residential data, daytime patterns of population density may not be well represented. This is particularly so in the CBD or other commercial or industrial districts within a city region. This is exemplified in Fig. 7 where population density for the Greater London area based on census data (Fig. 7a) and daytime working population (Fig. 7b) for 2001 is shown (ONS, 2010). The administrative unit used in Fig. 7 is 983 Middle Level Super Output Areas (MLSOA) which is a subdivision of the 33 local authorities. As the spatial pattern differs considerably between the two maps, caution needs to be exercised if a very fine spatial scale is chosen and the source of data needs to

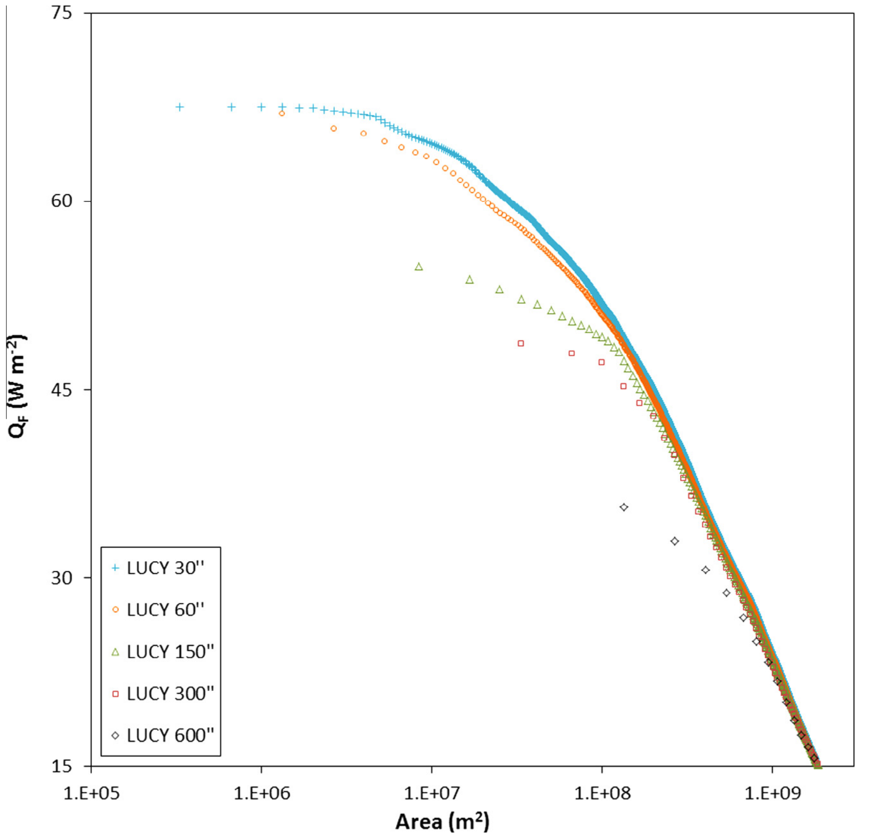

Figure 8. Cumulative Q_F sorted by area (cumulative average) for five different spatial resolutions within the Greater London area using the Global Rural–Urban Mapping Project (GRUMP) population density dataset.

be critically evaluated. For London, this is clearly the case (compare this to Fig. 2 in Hamilton et al., 2009 or Fig. 4 Iamarino, 2012).

In order to be able to examine the spatial distribution of population in more detail, an option to export a population density dataset as an ESRI ASCII grid at the scale modelled is included in LUCY v2013a. As LUCY is a global model, judgements on the balance between global coverage and accurate local data have to be made. In this case, the GRUMPv1 and GPWv3 datasets are the most appropriate to our knowledge. However, the possibility to include more detailed datasets to improve modelling capabilities is possible (see Appendix A).

Fig. 8 show the cumulative Q_F sorted by area (cumulative average) for five different spatial resolutions within Greater London using the GRUMP (v1) population density dataset. Sorting the data by ascending area and cumulatively calculating the spatially weighted mean shows clearly that as the total areas become larger the average fluxes become smaller. Comparing Q_F between the resolutions of 30″ and 60″, the maximum values of Q_F are almost similar whereas for the other resolutions the largest flux is smaller. In the former case, this is because the census data originate at borough level, which is much coarser than the original spatial resolution (30″) of the GRUMP dataset (see Fig. 6).

4. Anthropogenic heat flux change between 1995, 2005 and 2015

LUCY can be used to assess changes in the anthropogenic heat flux through time. Here the model is run for a 20 year period (1995–2015) at 10 year intervals. Changes in heat sources over this period have come about intentionally, for example local decisions to restrict vehicle use (Atkinson et al., 2009) or as a result of changes in building design (Eiker, 2009), and unintentionally (e.g., increasing population). For 1995 the data are almost complete, but for 2015 obviously the data need to be predicted. In the analyses presented here, the fraction of the vehicle fleet on the roads and the speed at which they travel is kept constant[1] (0.8 and 48 km h^{-1}, respectively; Allen et al., 2011). Weekly patterns (days of the week worked and hours of the workday) are held constant (Allen et al., 2011). The datasets used are:

(a) Global population density at 2.5′ × 2.5′ grid resolution (GWP, v3) for 1995, 2005 and 2015 (CIESIN, 2005).
(b) Energy consumption (EIA, 2012b) by country. For the year 2015 the trend of the most recent available period (1998–2008) is used to linearly extrapolate consumption for each country. Where these data are missing (Andorra and Liechtenstein), energy consumption from 1995 is used.
(c) Traffic information (United Nations Economic Commission for Europe, 2011) by country categorised into cars, motorbikes, and freight vehicles. However, these data are not complete and the census year varies by type between countries. For 2015, an annual change for the countries within the study area was estimated based on data between 2001 and 2009. Since the traffic data are sparse, an average change for the whole region was used for all countries.
(d) Mean monthly air temperature are from the Willmott et al. (2009) database at 0.5° × 0.5° for 1995 and 2005. To predict the impact of the future climatic conditions, a range of possible temperature extremes observed in Europe are used for 2015. These correspond to the 2006 temperature for summer (warmest in the dataset) and 1956 for winter (coldest).

Of interest here are urban areas in Europe (defined by the geographical coordinates 1°W to 27°E and 36°N to 63°N). The total urban area in this domain covers 482,286 km^2. Urban areas are designated based on a combination of population density, settlement points, and the presence of night time lights as described for the GRUMPv1 dataset (CIESIN, 2011). Both the spatial extent and location of urban areas are kept constant for the 20-year period considered here, but the population density

[1] In the UK for city roads (30 mph = 48 km h^{-1}) the number of vehicles exceeding the speed limit has decreased from 65% (2001) to 46% (2011) based on Department of Transport data. Decreases have also been recorded for motorways and dual carriageways (The Economist, 2013, p23).

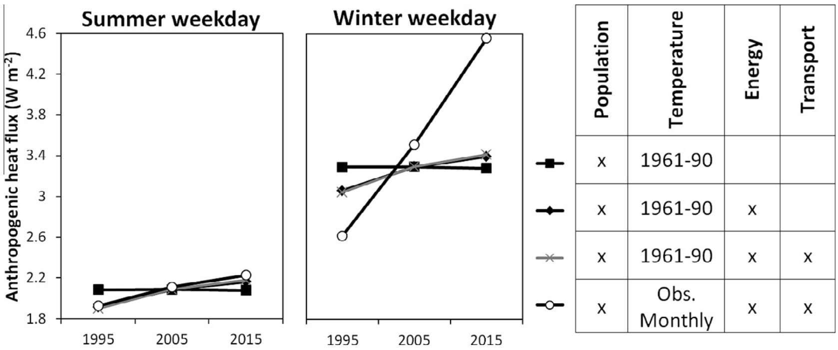

Figure 9. Anthropogenic heat flux for all urban areas in Europe for four cases (see text) on a weekday in summer and winter in 1995, 2005 and 2015.

changes. The 2015 data reflect trends based on the available data but do not include any policy changes that may lead to significant changes in energy use.

For the 20-year period, the changes in the key variables to the LUCY model for Europe result in differences from city to city. To explore this, two week (work) days, one each in summer and winter, are chosen to consider conditions when anthropogenic heat is expected to be greatest. The winter day is mid-February when there are few/no national holidays; the summer day is in mid-July. The effect of annual holidays which occur on different dates in different countries is not considered (see Allen et al., 2011 for impact). Four different cases are evaluated:

Case 1: Temperature data are the normal for 1961–1990 (Willmott et al., 1998); population data and predictions are from CIESIN (2005); and all other variables are kept constant at 2005 values.
Case 2: As for case 1, except energy consumption also is varied over the 20 year period.
Case 3: As for case 2, except traffic numbers also are varied over the 20 year period.
Case 4: As for case 3, except observed monthly temperature are used in calculations. For 2015, the warmest (July, 2006) and coldest (February, 1956) temperatures in the period 1901–2008 (Willmott et al., 2009) are used. Therefore, this is not a trend but the impact of extreme conditions within the observational record.

To demonstrate the effect of the different drivers (population, energy consumption, traffic, temperature) the mean anthropogenic heat flux for urban areas in Europe (as defined above) is calculated (Fig. 9). Obviously, the average is considerably smaller than the highest values as discussed in Section 3.

During the period 1995–2015, the overall population within the study area is predicted to decrease by 3.6%. The impact of this (case 1 – black squares in Fig. 9) is a decrease in Q_F in both summer and winter, though this decrease is less than 1% of the flux. The largest decrease is for the summer weekday (2.09 W m^{-2}).

A much more important impact results from the predicted changes in energy consumption (increase by 13.6% from 1995 to 2015). Given the decrease in population, these increases in energy consumption result from an even larger increase in energy use per capita. Considering the effect just of changes in energy consumption, the impact is predicted to be a 10–12% increase in Q_F for the two types of days considered (weekday summer/winter). The summer days have the largest increases (weekday largest, 13%) resulting from enhanced use of air conditioning.

The impact of accounting for the expected large increase in the volume of traffic is small (Case 3). However, as mentioned previously, much more of the traffic data are missing, hence there is greater uncertainty with this term. The overall annual change for cars, freight and motorbikes between 2001 and 2009 are 2.6%, 1.3% and −4.9%, respectively.

By far the largest impact relates to the temperature conditions (Case 4), as these influence the building energy use (mean weekday fluxes for 2015 in winter 4.56 W m^{-2} (Fig. 9) and summer

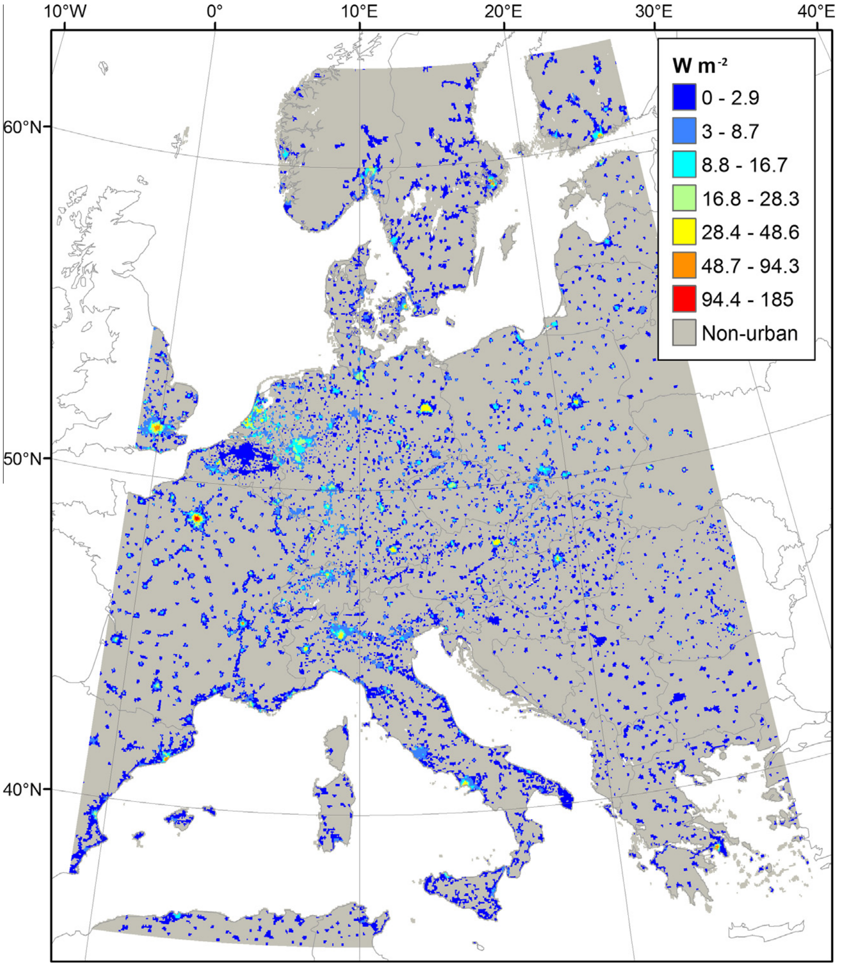

Figure 10. Daily average anthropogenic heat flux (W m^{-2}) on the 14th February 2005, Case 1 (see text). Natural breaks in ArcMap™ are used for the class breaks that best group similar values and maximize the differences between classes. Projection: Lambert Conformal Conic projection (Central meridian = 10°).

2.23 W m^{-2}). The temperature data used here for the past periods (1995, 2005) are the actual monthly mean air temperature, while the data for 2015 represent the extreme values in the record i.e., not an extrapolated trend. These fluxes are 42.5% larger than 2005 in winter and 13.5% larger in summer. While still small at the individual sites, aggregated over the entire urban area of Europe this represents a very large amount of additional energy that needs to be accounted for. Fig. 10 shows the spatial variability of Q_F during a winter weekday in 2005. Population distribution is an important factor in the spatial distribution of Q_F (Fig. 10). This is exemplified by comparing e.g., London and Paris, two similar cities based on size and population, but Paris is predicted to have a much higher peak in Q_F because of higher population density at its city centre.

5. Conclusions

The developments to the anthropogenic heat flux model LUCY (Allen et al., 2011) make it more responsive to temperature, a key driver of energy use and thus heat emissions. The changes described here also simplify user interaction with the model, and provide mechanisms to customise the input data. We hope that with analysis of more monthly energy consumption data, the temporal and spatial variations in energy use and temperature can be improved further. With the details provided here (Section 2) we hope individuals can provide either data for analysis and/or enhanced functions of new relations (Fig. 3) that will result in improved global modelling abilities.

The LUCY based calculations of the variability of the anthropogenic heat flux over a 20 year period for cities in Europe show that although the values on average are quite small they are significant in urban areas in the context of human induced global climate change. The results show that the changing energy use and the variability of air temperatures can result in large changes in the magnitude of Q_F. Considering the effect of only using changes in energy consumption over time, the impact is predicted to be a 10–12% increase in Q_F across the two types of days considered (weekday summer/winter). Clearly in other regions globally, with much larger increases in urban population (CIESIN, 2011) and energy use (EIA, 2012b), most notably in Asia and Africa, effects such as this will be even greater.

The importance of scale to the calculation of anthropogenic heat flux is demonstrated for London. It is absolutely critical that for any application, whether global climate modelling or sources of energy from buildings, the anthropogenic heat flux is calculated at the appropriate scale of the area of interest. A good understanding of the input data used is also crucial in order make accurate estimations of anthropogenic heat at different spatial scales.

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Appendix A. Mechanism to change or exchange input data

Users who want to complement or replace existing datasets available (e.g., with more up-to-date information or data from new sources), can do so using the London Urban Micromet data Archive (LUMA). Users can download and/or modify four types of data (annual energy consumption, population density, vehicle numbers and temperature) through LUMA. Information about the available data in LUMA is provided on the Urban Micromet webpage[2].

The procedure is shown in Fig. A1 (follow light grey arrows). The approach varies with data type. For data that are country and year specific a spreadsheet type format is used with four separate tables (worksheets); three for traffic and one for energy consumption. The online spreadsheets can be updated and altered by users to include missing data and/or new information. If a user adds new data into the database, both the provider and data source need to be specified. To use the spread sheets the selected data source needs to be saved as tab separated text files into the LUCY data folder (see Lindberg and Grimmond, 2013 for details).

The spatial data included in the datasets connected to LUCY are temperature and population data. Population datasets are stored as global datasets (85°N to 58°S) at 2.5′ × 2.5′ resolution or divided into 5° × 5° tiles with the spatial resolution of 30″ × 30″. Once an existing population dataset for a specific year is developed, the user needs to convert the dataset into MATLAB′s binary format (.mat) using the MCR program provided **mat2asc_v2013a.exe**. This program could be used to convert the common grid based format Esri ASCIIgrid (.asc) to the binary matlab format (.mat) as well as the other way around. The latitudinal and longitudinal extent of the datasets must be preserved based on the resolution using the WGS84 datum. To utilize a new dataset, for example population for an area of interest, the dataset first needs to be incorporated into the appropriate global (82°N to 58°S at 2.5′ resolution) or tiled (5° × 5° at 30″ resolution) spatial dataset at the correct resolution (see Lindberg and Grimmond, 2013 for details). The MCR program **mat2asc_v2013a.exe** can be used to obtain global or tiled grids where the values for the appropriate area should be substituted using almost any commercial or

[2] http://londonclimate.info.

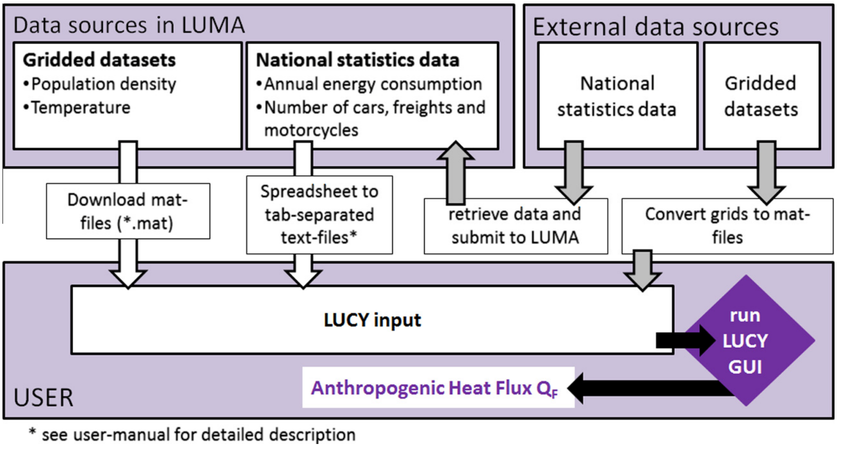

Figure A1. Flow chart of data exchange for open source LUCY application within the LUMA system.

open source GIS software. The new file needs to be converted to a binary mat-file and saved to the data folder for use with LUCY.

To include a daily temperature dataset the data need to be processed in the same way as for the population grids. Detailed instructions are provided in Lindberg and Grimmond (2013).

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