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Book or Report Section

Accepted Version

Chrysoulakis, N. and Grimmond, C. S. B. ORCID: https://orcid.org/0000-0002-3166-9415 (2016) Understanding and reducing the anthropogenic heat emission. In: Santamouris, M. and Kolokotsa, D. (eds.) Urban climate mitigation techniques. Routledge, pp. 27-40. ISBN 9780415712132 Available at https://centaur.reading.ac.uk/52736/

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Publisher: Routledge

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*Chrysoulakis N, Grimmond CSB **2016**: Understanding and Reducing the Anthropogenic Heat Emission **in** Urban climate mitigation techniques, (ed) M Santamouris, D Kolokots, Chapter 2:27-40 https://www.routledge.com/products/9780415712132, ISBN 9780415712132*

UNDERSTANDING AND REDUCING THE ANTHROPOGENIC HEAT EMISSION

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INTRODUCTION

Cities and the behaviour of their residents change through time. The spatial organization of urban areas, whether the footprint and height of buildings; the width, length, and layout of streets; where people live and where they work; the walkability and scale of neighbourhoods; the relative proximity of urban amenities; the type and diversity of urban green space all affect urban energy use. The global urban population is expected to increase up to 7 billion by 2050 (United Nations, 2010). Thus there are enormous opportunities to shape the built environment and for urban planning to play an important role in climate change mitigation (implementation of mitigation technologies, such as green roofs and cool materials) and adaptation (adaptation measures, such as emergency management plans) at the city level (Santamouris 2014). Mitigating climate change can be achieved better by regulating land-use change than CO_2 emissions reductions alone (Stone 2009). The regionalized impacts of the anthropogenic heat emissions on climate have the effect of more directly localizing the benefits of land-based mitigation (Stone et al. 2012).

One important challenge facing the urbanization and global environmental change community is to understand the relations between urban form, energy use and carbon emissions at different spatial and temporal scales. Yet, these types of analyses are needed by urban planners, who recognize that zoning a city at the local scale affects mobility and transportation choices, energy consumption and climate. As indicated by Seto and Christensen (2013), what is missing from most existing climate action plans is a clear link between urban land-use patterns beyond the individual parcel or building scale and energy use.

Energy enters passes and leaves a city in numerous ways and physical states and forms; for example, fossil fuels, electricity, radiation and heat. Construction materials, food, water and waste also store energy. What type of energy is considered depends on perspectives and applications. For example, urban planners, economists and statisticians, tend to focus on fluxes of energy that are “usable” for day-to-day activities and the optimization of this, with concern for questions such as how to influence energy consumption by administrative means, such as guidelines or regulation for insulation of new houses, traffic reduction etc. Meteorologists, in contrast, are more interested in understanding how energy in forms such as radiation and heat influences the urban climate and how it is transported and stored in the urban fabric and atmosphere. Energy flow charts by urban planners usually omit radiation and anthropogenic heat as a heating source (Chrysoulakis et al. 2009). Urban meteorologists, in contrast, consider them in the Urban Energy Budget (UEB), taking account of the anthropogenic heat resulting from vehicular emissions, space heating and cooling of buildings, industrial processing and the metabolic heat release by people.

The focus of this chapter is the anthropogenic heat flux, its quantification and significance and opportunities to moderate its effect on the urban climate.

QUANTIFYING THE ANTHROPOGENIC HEAT FLUX

Given the three dimensional nature of the urban ecosystem, the UEB approach considers a control volume, i.e. all terms in the balance equation represent fluxes into, or out of, or the storage change of this volume (Figure 1). The surface energy balance, with units of energy (J, joules) per unit time (s, seconds) per surface area (m^2), is defined for the top of the volume as:

$$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A + S \quad (J\ s^{-1}\ m^2 = W\ m^{-2}) \qquad (1)$$

where Q^* is the net all-wave radiation, Q_F is the anthropogenic heat flux, Q_H is the turbulent sensible heat flux, Q_E is the turbulent latent heat flux, ΔQ_S is the net change in heat storage within the volume (the volume is defined such that the flux into the ground is incorporated in ΔQ_S), ΔQ_A is the net advected flux ($\Delta Q_A = Q_{in} - Q_{out}$) and S represents all the other sources and sinks (e.g. heat removed by runoff, photosynthetic heat etc.); the heat-to-wastewater flux (Iamarino et al. 2011) is also included in S. This equation is applicable for small time steps (1 h), or if the UEB is integrated over the course of a 24-h period, the net storage term may be assumed small and ignored.

Significant advances have been made in the simulation of the physics of urban climate processes associated with enhanced computational capacity, improved Earth Observation (EO) sensors and model developments (Arnfield 2003, Weng 2009, Grimmond et al. 2010, 2011). Q_F is difficult to determine because of its strongly varying pattern and because it is very difficult to measure directly. Q_F consists of both sensible and latent heat components. Their relative importance varies not only with urban land use but also by time of year. In areas where evaporative towers are used in large cooling

systems the latent heat portion can be about 25% of total Q_F in summer; for example central Tokyo (Moriwaki et al. 2008) and Osaka Prefecture (Narumi et al. 2009, 23%).

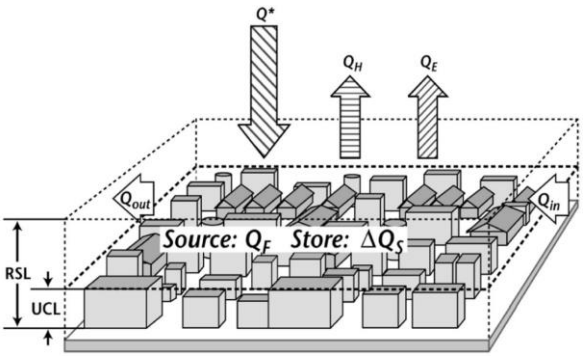

Figure 1. *Conceptual illustration of the fluxes in the energy balance of an urban building–soil–air volume (source: Roberts et al. 2006). UCL is the Urban Canopy Layer and RSL is the Roughness Sub-Layer.*

There are three general approaches to estimate Q_F (Sailor, 2011):

- *Inventories*: Commonly socio-economic data are used with energy use data to the three main contributors: mobile (e.g. traffic), stationary sources (buildings) and metabolic (human) release. The fraction of traffic as a function of type and amount of gasoline, the number of vehicles, their fuel efficiency and the distance they travel commonly are used. For stationary sources, consumer-scale long term data can be divided into short term fluctuations using large scale hourly variations of electricity/gas consumption (Grimmond 1992, Sailor and Lu 2004, Moriwaki et al. 2008, Hamilton et al. 2009, Smith et al. 2009). Recently, Iamarino et al. (2012) assessed the spatial variability of Q_F from buildings using high-resolution resident and workplace population data. They concluded that buildings are the major source of anthropogenic heat emissions, accounting for about 80% of the nearly 150 TWh of waste energy annually emitted across the Greater London. As discussed by Sailor (2011) such inventory approaches are limited by resolution. Typically, energy consumption data have good temporal resolution at coarse spatial scales, but poor temporal resolution at more detailed spatial resolution. In addition, assumptions have to be made about energy consumption and its relation to release and the location of the release (e.g. all to the external environment).

- *Residual of the UEB*: A second approach to estimate Q_F is to calculate the flux as the residual of the UEB (eqn 1). This is a more physically-based method all errors of the other terms are cumulated the residual flux. This method also assumes energy balance closure for the time interval of calculation. Measurements of the other UEB terms may have systematic biases, for example, if the turbulent heat fluxes are underestimated by the measurement technique (e.g. Eddy Covariance) or insufficient sampling (e.g. to obtain measurements to determine the storage or radiative fluxes). To simplify, the problem long time periods are used, so storage term can be assumed to be negligible (Pigeon et al. 2007). Furthermore, there is the incorrect assumption that all the UEB fluxes are commonly measured at the same spatial scale. The high level of uncertainty associated with residual Q_F means both the temporal and spatial resolution are coarse (of the order 10^2 – 10^3 m) and diurnal profiles cannot be resolved. Thermal remote sensing may have the potential to improve this approach (see, for example, Kato and Yamaguchi 2005, 2007, Rigo and Parlow 2007, Kato et al. 2008, Xu et al. 2008).

- *Building energy models:* As the release of anthropogenic heat is typically largest from the building sector, it has been the subject of many focused studies. These bottom-up studies generally involve explicit modelling of energy consumption within buildings and careful evaluation of heat emissions. Typically prototypes buildings are modelled using detailed building energy simulations. These results can then be integrated with an urban canopy meteorological model, which for completeness requires the other two components of Q_F to be accounted for (transport and metabolism). The building energy sub-models explicitly account for building occupants, radiative transfer through windows, type of air-conditioning heat exchanger (air-cooled vs evaporatively cooled) and performance of air-conditioning systems, in addition to the building shape, materials, etc. The use of such a detailed building energy sub-model results in more realistic estimate of anthropogenic emissions (Kikegawa et al. 2003, Sailor 2011, Bueno et al. 2012). For the most part, these building sector prototype approaches have focused on generating representative profiles of anthropogenic emissions of heat and moisture rather than broader estimates. Only recently have the models been dynamically linked with urban atmosphere models (Sailor 2011, Bueno et al. 2012). These can provide data at high spatial and temporal resolution but the contribution of transport is ignored.

A better understanding of local scale interactions between typical urban units and the atmosphere is needed for both urban planning and landscaping and climate mitigation strategies. In particular, the key characteristics governing energy exchange between the surface and atmosphere have to be identified if adequate action is to be taken to improve thermal comfort, reduce energy use, or reduce the impacts of extreme heat/cold events. Such knowledge is also critical for a better characterization of boundary layer processes and therefore for applications in the fields of air quality and pollutant dispersion. In many cases the release of this heat is also associated directly (e.g. vehicles) or indirectly (e.g. buildings) with pollutant release, whether the greenhouse gas of carbon dioxide or small particulates (e.g. PM_{10}). Thus changes in energy use and heat release may also change the pollutants that are released and/or the location of their release.

THE IMPORTANCE OF THE ANTHROPOGENIC HEAT FLUX

Nearly all energy used for human purposes is dissipated as heat within the Earth's surface-atmosphere system. Thermal

energy released from non-renewable sources is therefore a climate forcing term. Flanner (2009) estimates that averaged globally this forcing is only +0.028 W m^{-2}, but over the continental United States and Western Europe, it is +0.39 and +0.68 W m^{-2}, respectively. The anthropogenic heat flux emission is though strongly affected by climate and weather, because this determines whether heating or cooling systems are used. In the USA, between 60 and 70% of energy consumption in buildings is used for heating, air-conditioning and water heating (Heiple and Sailor, 2008). While predicting climate change and its impacts at a global scale has uncertainties, local effects of urbanization on the climate have long been documented. Recent work has documented that most large U.S. cities are warming at double the rate of the planet as a whole, a trend attributed to rapid growth in the UHI phenomenon (Stone et al. 2012). Urban warming has important implications for human comfort, health and well-being. Many examples exist of the vulnerability of urban populations, most often young children, the elderly and the poor, associated with heat waves; for example in Chicago (1995), India (1998), France, Spain and UK (2003) and Russia (2010). Future climate scenarios, which predict an increase in summertime maximum temperatures and also in the frequency and magnitude of extreme conditions, suggest greater risks for vulnerable people in the future. Warmer conditions in cities will also increase demand for air conditioning. More air conditioners generate more heat and have significant effects on the local-scale external climate, with implications for human comfort and the demand for cooling. At a larger scale, greater use of air conditioning results in more greenhouse gases through increased electricity generation. Concurrent with rising heat wave activity also is a growing incidence of heat related health effects among urban populations and more frequent failures of critical infrastructure, such as electrical power generation and transmission systems. Confronted with these trends, many urban governments have revised or developed new heat wave emergency response plans, as part of broader climate change mitigation and adaptation strategies. This has broader implications in terms of the management of energy resources to reduce Q_F.

Q_F varies widely through the year, through the day, between countries and urban areas. Although typical values in cities range from 5 - 100 W m^{-2} (Christen and Vogt 2004, Allen et al. 2011), very high Q_F values under extreme localized conditions have been reported. In a modern city core with high-rise buildings and intense traffic, Q_F can exceed 100 W m^{-2}; for example Q_F values up to 550 W m^{-2} for London (Iamarino et al. 2012). Furthermore, changes in energy consumption due to changes in climate are predicted to cause a 13% (11%) increase in Q_F on summer (winter) weekdays in Europe (Lindberg et al. 2013). The largest impact results from changes in temperature conditions, which influences building energy use. The spatial resolution used to model Q_F is critical and highlights implications for scientific understanding and decision making. High resolution databases (100 m x 100 m) typically are only developed for individual cities or small areas within them (Lindberg et al. 2013). At the other extreme are the global (0.5° x 0.5°) datasets; for example Flanner (2009).

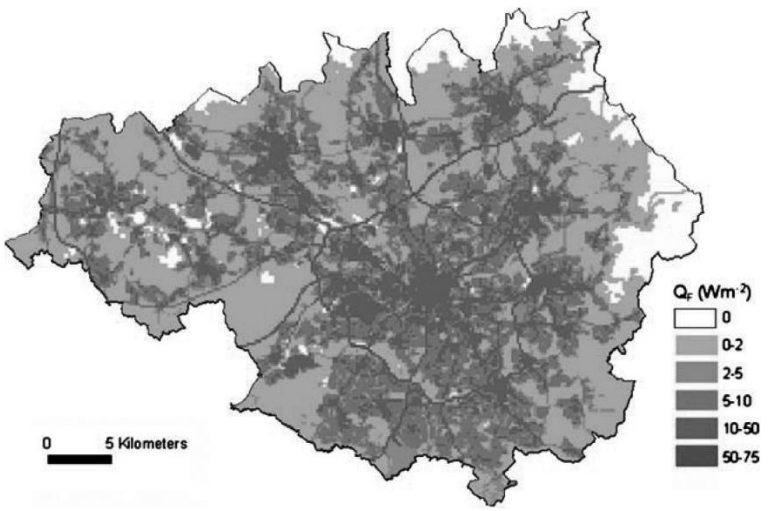

Figure 2. *Daily averaged Q_F (W m^{-2}) estimates for Greater Manchester at 200 m x 200 m grid, using urban morphology units (source: Smith et al. 2009).*

The magnitude of Q_F is highly dependent on the spatial scale at which it is estimated. In cities, peak values are associated with large buildings and busy roads. Smith et al. (2009) estimated Q_F spatiotemporal patterns for the city of Manchester at 200 m x 200 resolution, using a top-down approach based on urban morphology units. Their daily averaged Q_F estimates (Figure 2) highlighted the potential for exposure to localized heat sources which may lead to additional thermal discomfort and overheating during the summer months; and conversely the potential for lowered energy consumption due to a decrease in heating demand in urban centres during winter. Lindberg et al. (2013) employed the Large-scale Urban Consumption of energY (LUCY) model to estimate the spatial distribution of Q_F across Europe for the period 1995 - 2015, considering changes in temperature, population and energy use. They found that while on average Q_F was small (of the order 1.9 - 4.6 W m^{-2} across all the urban areas of Europe), significant spatial variability existed (maximum 185 W m^{-2}). Therefore, while still small at the individual sites, aggregated over the entire urban area of Europe Q_F represents a large amount of additional energy that needs to be accounted for in considerations of urban energy exchanges, as shown in Figure 3 (Lindberg et al. 2013).

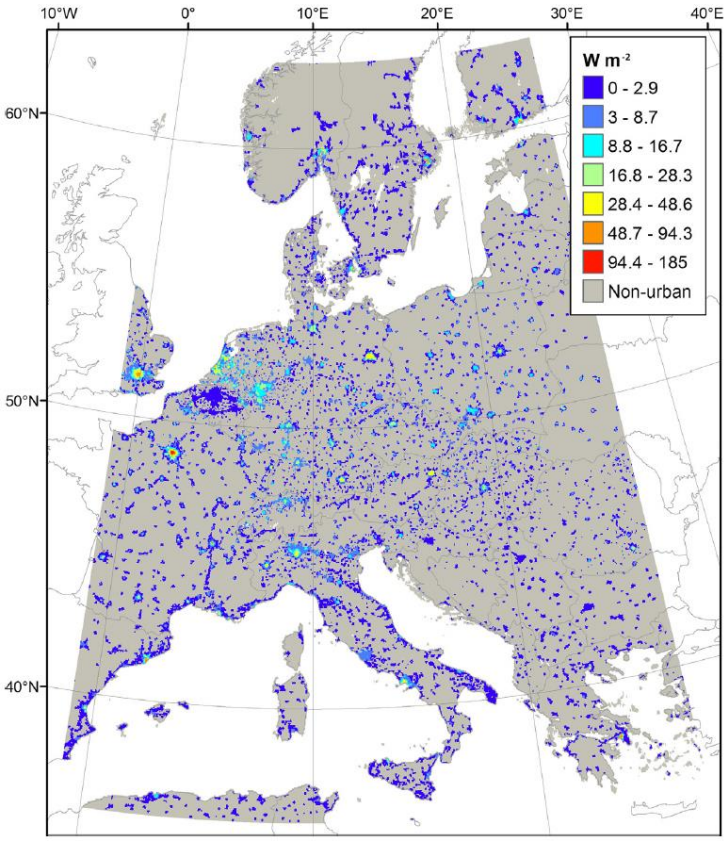

Figure 3. *Daily averaged Q_F (W m^{-2}), based on LUCY (Large-scale Urban Consumption of energy) model simulations for 14th February 2005. Population distribution is an important factor in the spatial distribution of Q_F. This is exemplified by comparing e.g., London and Paris, two similar cities based 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 (source: Lindberg et al. 2013).*

In terms of its temporal variability, as a general rule, the diurnal profile of total anthropogenic heating has local peaks in the early-morning and late-afternoon, corresponding to peaks in transportation and building energy use. However, in commercial and industrial areas these peaks maybe less obvious. Grimmond et al. (2010) argue that Q_F may become especially significant in the UEB at key times of the day and night and specifically at transition times. As illustrated in Figure 4 (Sailor 2011), the diurnal profile also depends upon the day of the week, with total emissions on weekends and holidays significantly lower than emissions on workdays. The relative magnitude of the morning and evening peaks depends upon the underlying climate and the season. In summer, the afternoon peak becomes more pronounced as a result of air-conditioning loads that tend to peak between 15:00 and 17:00 local time. In the winter, the morning peak may become more pronounced as a result of heating demand in the building sector. Therefore, producing local scale spatially and temporally resolved Q_F profiles would be of value not only for inclusion to, and the evaluation of, UEB models, but also for use by urban planners and designers to understand and better manage the future impacts of a changing climate on patterns of risk within urban populations.

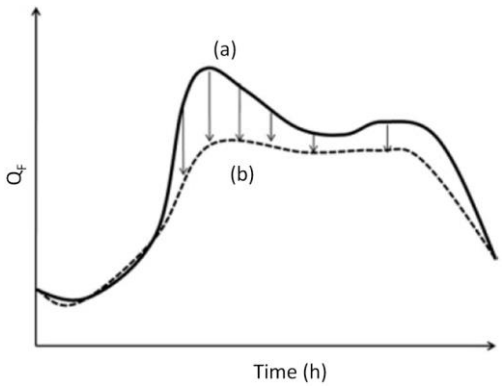

Figure 4. *Typical shapes of diurnal profiles of anthropogenic heating for (a) work days, and (b) non-work days, illustrating local peaks in the morning and early evening hours (adapted from Sailor 2011).*

The sensible anthropogenic heat emissions can lag the timing of the energy consumption and can differ substantially in magnitude. The bulk of the discharge from transportation is directly into the atmosphere and without significant time lag. As a consequence, profiles of energy generation from road fuels and atmospheric heat emissions are coincident, and the same applies to metabolic emissions from people outdoors. This is not true for the energy consumed in buildings and the metabolic emissions from people within because of the heat transfer resistance between buildings and atmosphere and the thermal inertia of buildings. Moreover, the total energy exchanged by the buildings with the atmosphere can be larger than just the anthropogenic sources in buildings, because it also includes the short-wave and long-wave radiation absorbed by buildings less the heat dissipated into the ground. Because of this, the total energy exchanged by the buildings with the atmosphere is not equivalent to the energy consumption in buildings (Iamarino et al. 2012).

Anthropogenic moisture emissions also take two forms. Heat removed from buildings can be exhausted through evaporative cooling equipment. Such heat removal is often referred to as anthropogenic latent heating, with the net effect on the urban atmosphere also being a source of moisture. The second mechanism of anthropogenic moisture emissions is the chemical reaction that occurs in the combustion of hydrocarbon fuels either in vehicle engines or combustion furnaces. This process creates anthropogenic water vapour as a result of a chemical reaction rather than phase change and is thus distinct from latent heat emissions. Usually, the term anthropogenic heat is used to refer to sensible emission of heat associated with energy consumption. The latent and chemical generation of anthropogenic moisture resulting from energy consumption in the urban environment is referred to collectively as anthropogenic moisture emissions. Sailor et al. (2007) estimated that, due to significant environmental loads, heat emission from buildings can be 50 to 100% greater than the energy consumption of the building. They also found that an important percentage of the heat emitted from buildings in the commercial core of a city such as Houston (with large buildings with evaporative cooling towers) is emitted as latent heat.

ANTHROPOGENIC HEAT FLUX and LOCAL CLIMATE ZONE

Knowledge of Q_F at the local scale is important in Local Climate Zones (LCZ) identification. Stewart and Oke (2012) formally defined LCZ as regions of uniform surface cover, structure, material, and human activity that span hundreds of metres to several kilometres in horizontal scale. LCZs simplify the broad variety of urban forms into 17 categories that are characterized by building morphology, roads, plants, soils, rock, and water. Descriptive sheets of the LCZ classes include images to enable the general urban forms to be recognized. Obviously not all urban areas fit perfectly into a LCZ and there are areas of transition. LCZ classes are local scale units, a minimum areal extent of the order of 400 – 1000 m, with dimensions based on the length scales that are needed for the atmosphere to develop an internal boundary layer that is adjusted in response to surface features of the LCZ. Close to the upwind edge of the LCZ, the depth of this layer will be shallow but will develop with distance into the LCZ. This scale is common to urban planning scales. Thus LCZ system has the potential to support well-established planning projects such as Climatope Maps (Scherer et al. 1999) and Urban Climatic Maps (Ren et al. 2011). To help quantify the thermal and morphological layers of an urban climatic map, standardized metadata for urban structure, cover, fabric and metabolism can be extracted from the LCZ. Bechtel and Daneke (2012) have shown that LCZ can be determined using multiple earth observation (EO) data sources by defining five properties: the sky view factor; the fraction of impervious materials; the terrain roughness; the surface thermal admittance; and the mean annual Q_F. LCZs can help to identify the key processes governing the partitioning of energy at the urban surface and they also provide guidance as to what sort of Q_F values should be expected for a particular area where surface characteristics are known.

METHODS AND TECHNOLOGIES TO REDUCE ANTHROPOGENIC HEAT EMISSION

Recent research has permitted the development of technological countermeasures to the impact of urban warming. Mitigation techniques aim to balance the thermal budget of cities by increasing thermal losses and decreasing the corresponding gains. As a variety of factors (e.g. surface cover, anthropogenic heat release and urban characteristics including morphology, geographic features and climatic conditions) interact with one another to generate the UHI effect, a range of measures are needed to be effective. Among the more important of the UHI mitigation techniques are those targeting the increase the albedo of the urban environment, to expand the green spaces in cities and to use the natural heat sinks in order to dissipate the excess heat strength (Santamouris 2014). Strategies for mitigation of UHI effects should therefore include measures related to: a) urban morphology and structure; b) urban materials; and c) reduction of Q_F.

Table 1. *Categories of Q_F reduction measures (adapted from Yamamoto 2006).*

Measure	Action
Improvement in the efficiency of energy-using products	Office automation equipment and electric consumer applications
Improvement in the efficiency of air-conditioning systems	Refrigerators and heat sources equipment
Optimal operation of air-conditioning systems	Proper placement of outdoor units
	Use of cooling towers
	Voluntary restraints on night-time operations
Improvement in the heat insulation and thermo-shield of buildings	High-performance heat insulation materials (interior heat insulation materials)
	High-performance heat insulation and thermo-shield materials (exterior heat insulation materials)
Greening of buildings and adoption of water-retentive materials	Greening of buildings and adoption of water-retentive materials (exterior heat insulation materials)
Improvement in the reflectivity of walls and roofing materials	Light coloured walls and highly reflective roofing materials
Introduction of traffic control measures	Traffic demand management and introduction of low emission vehicles
	Promotion of alternatives such as bicycles
Introduction of district heating and cooling	Central control of exhaust heat from buildings (at the regional level)
Use of untapped energy	Use of sea, river and ground water
	Use of exhaust heat from urban facilities (use of exhaust heat from industrial plants, subways, buildings, power plants, substations etc.)
	Recovery of energy from waste materials (waste power generation and heat supply)
Use of natural energy	Photovoltaic generation
	Use of solar heat

From the perspective of urban planning and design, urban planners should focus on the determination of appropriate parameters and practices, which can be modified based on technological interventions capable of reducing Q_F. Therefore parameters (relative to buildings and urban design) and practices (relative to traffic) can be determined in each city, and technological solutions may be proposed on their modification towards reducing the anthropogenic heat. For example, parameters relative to buildings include ventilation, shading, use of appropriate covering materials and relative position

with regards to heat sources. The scale, at which interventions for the reduction of anthropogenic heat will be implemented, should be also defined. At local scale (neighbourhood), technologies focus on urban micro-climate and urban design. At building scale, they focus on optimization of radiation and air fluxes. At micro-scale, they focus on thermal comfort and on impacts on human health. The selection of appropriate technologies must be based on international and local practices and resources. The potential of each technology for an area, for different scales, should be evaluated. For example, at micro- or building-scale the increase of the shading by trees and reduction of surface temperature through greening rooftops and walls; and at local scale, the increase of urban density with building orientations, through the appropriate planning and design. The Q_F reduction measures that are considered most effective, as summarised by Yamamoto (2006), are shown in Table 1.

A challenging aspect of assessing the impact of Q_F on thermal comfort is the estimation of the actual location of the emissions from buildings. Some of the anthropogenic emissions occur as conduction through the building envelope. A larger fraction occurs as a result of air exchanges through the facade and through natural operation of windows and doors. The largest fraction of anthropogenic emissions from buildings comes in the form of heat and moisture removed by mechanical heating, cooling, and ventilation systems. It is thus important to know where these systems are located. As discussed by Sailor (2011), in buildings that are fewer than 10 stories tall, the heating, ventilation and air conditioning equipment may be located adjacent to the building on the ground level, on a mezzanine-level roof, or on the rooftop of the top floor. In mid- and high-rise commercial buildings, however, the emissions may be more uniformly distributed vertically on utility floors, or consolidated at the rooftop level.

Priority for implementing UHI mitigation measures has commonly been given to measures that are readily available, but there is a growing need to adopt long-term, large-scale measures. The short term, small-scale measures now being implemented are not always delivering the hoped-for results (Yamamoto 2006). For this reason the planning community need spatially disaggregated Q_F data, at neighbourhood and city scales. Such information is practically impossible to derive by point *in-situ* fluxes measurements, while satellite remote sensing potentially is a valuable tool for estimating UEB parameters (e.g. albedo, surface cover) exploiting EO data. Currently estimation of Q_F spatial patterns are a challenge but the expected near future satellite data maybe allow new methods to be developed to estimate the spatiotemporal patterns of all the UEB fluxes, including Q_F. These techniques would allow benchmarking of current conditions so assessment of interventions can be made to ensure that the expected benefits are obtained. EO can directly support urban planning (Chrysoulakis et al. 2013b), map surface morphology and characteristics, and evaluate the implementation of UHI mitigation technologies (Mackey et al. 2012).

Systematic effort towards of heat emissions reduction at local level is needed, as climate change mitigation policies may reduce CO_2 emissions at the point of energy production, but not necessarily heat emissions associated with the user. This implies that Q_F will continue to contribute to thermal discomfort and overheating (Smith et al. 2009). Understanding Q_F spatiotemporal patterns is expected to lead to the development of more efficient methods and techniques for Q_F reduction in cities, supporting the mitigation of the UHI effect and improving thermal comfort

FINAL COMMENTS

Anthropogenic heat emissions produced by human activities are one contributor to the UHI. Q_F sources include heat generated by the combustion process in vehicles, heat emitted 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. The flux is strongly affected by climate and weather as this determines if heating or cooling systems are used. While Q_F varies spatially and temporally (diurnally, seasonally and yearly), under many conditions it can exceed energy receipt from net all-wave radiation. Its diurnal profile depends upon the day of the week and has local peaks in the morning and mid-afternoon, corresponding to peaks in transportation and building energy use. Q_F commonly is omitted from climate models despite its local importance (Allen et al. 2011). For this reason the Earth system modeling community needs spatially disaggregated Q_F data, at local and city scales. The estimation of Q_F spatiotemporal patterns is therefore a major challenge, which EO may be able to contribute to.

Knowledge of Q_F patterns is important for urban planning (e.g. to reduce or prevent QF hot spots), health (e.g. to estimate the impact on thermal comfort) and future proofing (e.g. to plan and implement interventions towards Q_F reduction in these areas). Planning tools, such as Urban Climatic Maps and Climatope Maps, should be enriched with information on Q_F patterns. Mapping provides visualization of assessments of these phenomena to help planners, developers and policy makers make better decisions on mitigation and adaptation. The recently developed concept of LCZ (Stewart and Oke 2012) provides a means to better integrate Q_F in urban climate mapping.

Knowledge of the spatial and temporal patterns of Q_F are still prone to large uncertainties. Additionally a better understanding of the impact of Q_F on urban climate is needed as the impact overlaps at several scales: regional and meso-scale processes, plus within the street canyon and rooftop, and within the building. Better integration of the different estimation methods (*in-situ* measurements, modelling and remote sensing) would permit the respective strengths to be used and potential to overcome the weaknesses of individual methods. There is potential for EO to support our understanding of the role of Q_F within the UEB but this remains underexploited. As Q_F is directly linked to urban

metabolism, it was explored within the EU FP7 project BRIDGE (Allen et al. 2011, Iamarino et al. 2012, Kotthaus and Grimmond 2012, Chrysoulakis et al. 2013a, Kotthaus and Grimmond 2013, Lindberg et al. 2013). It is clear that the reduction of Q_F through interventions targeting urban metabolism optimization should be among the objectives of sustainable urban planning.

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