Estimating anthropogenic heat release from megacities

Iain Stewart[1], Chris Kennedy[1]
[1]*University of Toronto, Toronto, Canada, iain.stewart@utoronto.ca*

Iain D. Stewart

1. Introduction

All cities emit heat into the planetary boundary layer. A small but important source of this heat is human activity and its associated burning of fossil fuels for urban transport, industrial processing, and domestic heating and cooling (Oke, 1982). Combustion processes in cities set the anthropogenic heat flux, which is an important forcing term in models of the urban heat island effect and global climate change (Allen et al., 2011; Flanner, 2009). In perhaps the earliest study to quantify the thermal effects of human activity on urban climate, Eaton (1877) calculated the heat released from coal combustion in the Metropolitan District of London in the late nineteenth century. Accounting also for the 'vital heat' of the city's 3.5 million inhabitants, Eaton predicted these sources to raise the air temperature in London by 1.4 K (cited in Garnett and Bach, 1965). In a more detailed study, Ichinose et al. (1999) used numerical models to simulate air temperature changes of > 2 K by these same effects during winter nights in central Tokyo.

Published estimates of anthropogenic heat release originate mostly from wealthy, mid-latitude cities such as Tokyo and London, with few comparable estimates from cities of tropical or low-income regions. The literature could therefore profit from a universal set of anthropogenic heat flux densities representing cities of diverse geography, and having consistent methods of derivation. Herewith, we initiate the development of such a dataset. Using an inventory approach, we calculate heat flux densities at metropolitan scale for the world's 27 megacities, i.e., urban agglomerations of more than 10 million people. The global distribution of these cities—and our use of a common methodology—allows for regional insight into the economic, climatic, and demographic influences on anthropogenic heat release in urban environments.

2. Definitions, methods, and data sources

We define 'megacity' as an urban agglomeration that houses > 10 million people and that captures a commutershed of common labour and real estate markets. Megacities include a densely populated core city, as well as satellite cities and adjacent peri-urban and rural lands. As of 2010, there were 27 megacities in the world (http://www.citypopulation.de/world/Agglomerations.html); more than one-half of the megacities are located at tropical and subtropical latitudes of Asia, Africa, and Latin America (Table 1).

Anthropogenic heat release from cities (Q_F) is a key term in the urban energy balance equation, and is the sum of three component terms:

$$Q_F = Q_{Fb} + Q_{Fv} + Q_{Fm}$$

where all terms are heat flux densities per unit area (W m^{-2}): Q_{Fb} is heat from electricity use and combustion of domestic and industrial fuels in buildings; Q_{Fv} is heat from fuel combustion in ground vehicles; and Q_{Fm} is heat from human and animal metabolism. Contributions from Q_{Fm} are minor in most cities, amounting to less than 10 % of total Q_F (Sailor and Lu, 2004). Q_{Fm} is thus routinely omitted from models of urban energy balance and global climate change.

We used an inventory approach to estimate total Q_F for each megacity. The inventory approach equates sensible heat release with energy consumption; heat released through water vapour and wastewater systems is therefore not treated here. Although this approach yields results that are temporally and spatially coarse, it is favoured because population and energy consumption data are available for most cities, and are amenable to inter-city comparison and urban climate modelling (Sailor and Lu, 2004).

We sourced population and energy consumption data from the 'Metabolism of Megacities' dataset housed at the University of Toronto (Table 1). The dataset includes metropolitan-level totals for energy, water, waste, and material flows for the world's 27 megacities. Raw data were gathered from a network of megacity researchers and subsequently analysed at the University of Toronto for use in a major international study of urban resource flows (Kennedy et al., 2015). All data were conveyed in standardized format and with supplementary information on (i) the biophysical attributes of each city, and (ii) the role of utility

Table 1 Geographic and socio-economic metadata for the world's megacities in 2011. Data ordered by population.

Megacity	Latitude	Pop.[a] (10^6)	Land area (km^2) Total	Urban	Urban density (capita km^{-2})	Income[b] group	Energy use[c] (GJ capita^{-1} yr^{-1})
Tokyo	35° 41′ N	35.6	13,559	6,993	5,094	H	71.9
Shanghai	31° 12′ N	23.5	6,341	3,820	6,145	U/M	90.3
New York	40° 42′ N	22.2	29,654	10,343	2,148	H	127.2
Lagos	6° 27′ N	20.5	2,798	1,000	20,555	L/M	29.7
Cairo	30° 3′ N	20.5	17,393	1,573	13,026	L/M	18.6
Beijing	39° 55′ N	20.2	16,411	3,377	5,977	U/M	69.3
São Paulo	23° 33′ S	19.8	7,947	1,957	10,127	U/M	29.0
Osaka	34° 41′ N	17.1	14,909	3,200	5,340	H	75.9
Delhi	28° 36′ N	16.8	1,483	1,114	15,044	L/M	13.7
Dhaka	23° 42′ N	15.6	1,860	911	17,135	L	25.4
Karachi	24° 51′ N	15.5	3,527	2,000	7,750	L/M	20.5
Kolkata	22° 34′ N	14.1	1,887	531	26,577	L/M	4.9
Istanbul	41° 00′ N	13.5	5,461	1,360	9,914	U/M	37.5
Buenos Aires	34° 36′ S	12.8	3,209	2,477	5,170	U/M	53.8
Guangzhou	23° 08′ N	12.8	7,434	3,843	3,318	U/M	90.3
Mumbai	18° 58′ N	12.5	603	255	48,893	L/M	8.6
Tehran	35° 41′ N	12.2	18,900	1,390	8,765	U/M	91.2
Rio de Janeiro	22° 54′ S	11.9	5,328	1,084	10,986	U/M	30.6
Manila	14° 35′ N	11.9	636	636	18,641	L/M	47.0
Paris	48° 51′ N	11.9	12,011	2,535	4,676	H	63.2
Moscow	55° 45′ N	11.5	1,080	737	15,609	U/M	146.6
Seoul	37° 34′ N	10.5	606	363	28,994	H	77.4
Shenzhen	22° 33′ N	10.5	2,020	1,992	5,256	U/M	n.a.
Los Angeles	34° 03′ N	9.9	10,518	3,500	2,825	H	104.0
Jakarta	6° 12′ S	9.8	662	556	17,601	L/M	38.8
Mexico City	19° 26′ N	8.9	1,495	792	11,170	U/M	47.6
London	51° 30′ N	8.2	1595	560	14,594	H	87.7

[a] Population surveyed in the energy and material flow analysis of Kennedy et al. (2015)

[b] Country income group in 2011 based on gross national income (World Bank): H—high; U/M—upper middle; L/M—lower middle; L—low

[c] Annual per capita energy use in 2011 (Kennedy et al., 2015)

companies to provide basic services such as sewerage, grid electricity, and solid waste collection. In some cases, the metabolism data were reported for populations below the megacity level, and thus do not capture the extended metropolitan region (e.g., Seoul, Mumbai, Manila, London, Los Angeles, Mexico City).

We determined Q_{Fb} from the sum consumption of (i) building fuels for home and industry, and (ii) building electricity for lighting, cooking, heating/cooling, etc. Q_{Fv} was calculated from the consumption of transportation fuels in cars, buses, and other ground vehicles. To calculate Q_{Fm}, we assumed an average caloric intake of 3,000 kcal day^{-1} capita^{-1} (World Health Organization, 2003). This equates to a bodily heat release of ~ 150 W capita^{-1}. For completeness, we also included heat release from urban animals, estimated to be one-quarter of that released from humans, or ~ 40 W animal^{-1} (Garnett and Bach, 1965; Oke, 1987). More difficult to estimate is the number of animals in megacities (e.g., urban livestock, roaming dogs, companion pets). In the megacity of Dhaka, Schlere and van der Hoek (2001) estimated the animal-to-human ratio to be 8:10. In other regions, the urban dog-to-human ratio is 1:10 in Los Angeles (Found Animals Foundation, 2009), 1:6 in Lagos (Hambolu et al., 2014), and 1:4 in São Paulo (Alves et al., 2005). On these accounts, we set the animal-to-human ratio in megacities to vary with country income: in high-income regions, the ratio is 1:10; in upper-middle income, 4:10; in lower-middle income, 7:10; and in low-income, unity.

3. Results

Relative to the total land area of each megacity, annual Q_F values for 2011 range from 1 W m^{-2} in Cairo to 51 W m^{-2} in Moscow (Fig. 1). This range reflects the variably sized areas reported for each megacity (Table 1). Paris, Tehran, Osaka, Tokyo, Beijing, Cairo, New York, and Los Angeles are the largest megacities by area, and have the highest per capita energy use (notwithstanding Cairo), but their Q_F values are relatively low because heat is released across a large metropolitan region. High Q_F values in Seoul and Moscow are due to high population densities and high per capita energy use. In megacities with low per capita energy use but high population density, Q_F values remain above average (e.g., Manila, Jakarta).

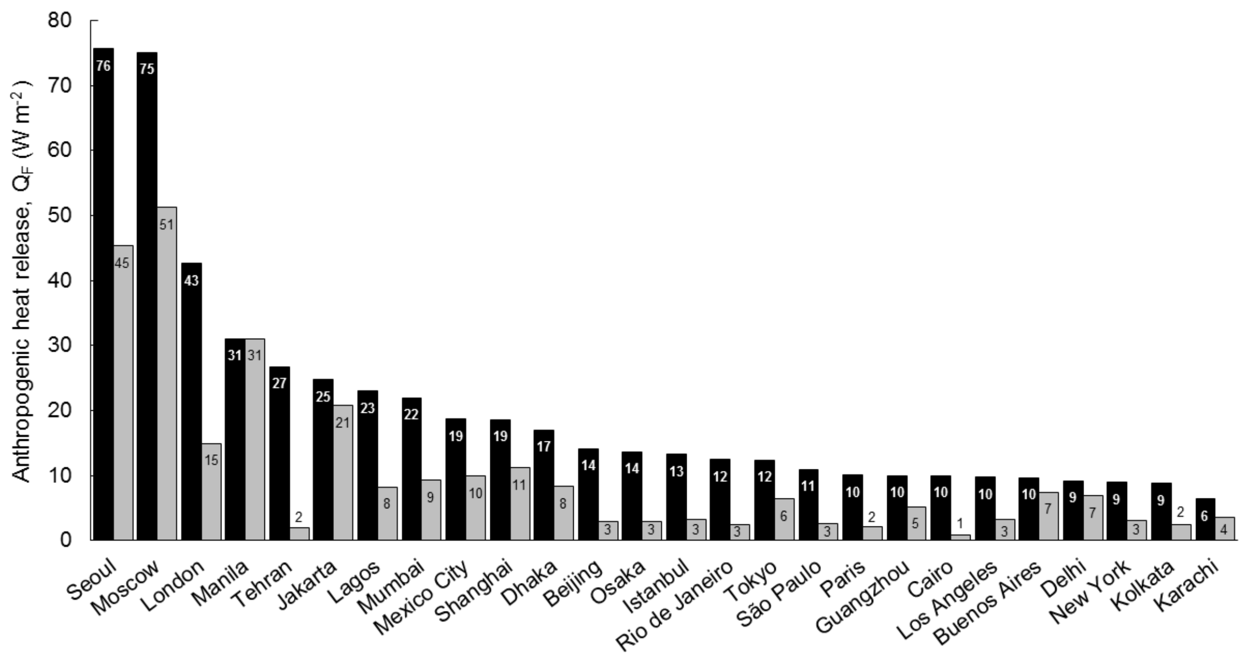

Fig.1 Annual anthropogenic heat release (Q_F) from megacities in 2011. Shenzhen excluded due to erroneous data. Grey bars = *Q_F from total land area;* black bars = *Q_F from urban land area.*

To reduce spatial coarseness in the Q_F values, we calculated heat flux densities per urban land area (Fig. 1). In this calculation, we assumed that heat release in megacities is mainly from the built-up areas. Q_F values in Kolkata (9 W m^{-2}), Cairo (10 W m^{-2}), Paris (10 W m^{-2}), São Paulo (11 W m^{-2}), Rio de Janeiro (12 W m^{-2}), Istanbul (13 W m^{-2}), Osaka (14 W m^{-2}), Beijing (14 W m^{-2}), and Tehran (27 W m^{-2}) increase markedly because the urban areas are much smaller than total land areas. Seoul and Moscow retain the highest Q_F values of the group, at ~ 75 W m^{-2}, due to their high population densities and cold continental climates, which drive heating and industrial fuel use.

Heat release from the building sector (Q_{Fb}) amounts to more than 50 % of total Q_F in all megacities except Mexico City, São Paulo, Mumbai, Kolkata, and Delhi (Fig. 2). Waste heat from electricity use contributes 21 %, on average, to Q_F, and ranges from 1 % in Lagos to 37 % in Osaka. Low values for Lagos (1 %) and Dhaka (7 %) are an indication of poor economies that lack electrical grids. Contributions to Q_F from domestic and industrial fuel use range from 4 % in Kolkata to 77 % in Lagos. Both cities have tropical climates and low-middle income economies, but differ in final energy carriers: in Lagos State, the main carrier is biomass (e.g., charcoal, fuel wood), whilst in Kolkata, it is electricity (coal-generated). In Moscow, Seoul, London, and Tehran—the world's coldest megacities—domestic and industrial fuel use accounts for more than 50 % of Q_F. This equates to Q_{Fb} values that exceed total Q_F values in the three South American megacities.

The contribution of ground transportation heat (Q_{Fv}) to total Q_F varies broadly about the group mean of 23 % (Fig. 2). In the emerging economies of Brazil, China, and Indonesia, where growth in car ownership is outpacing that of transportation infrastructure, Q_{Fv} accounts for 30 to 40 % of total Q_F. In the wealthy and sprawling megacities of Los Angeles and New York, the contributions are 27 and 36 %, respectively. Lower-income megacities like Manila, Cairo, Lagos, and Dhaka have Q_{Fv} values contributing < 7 % to Q_F. In the

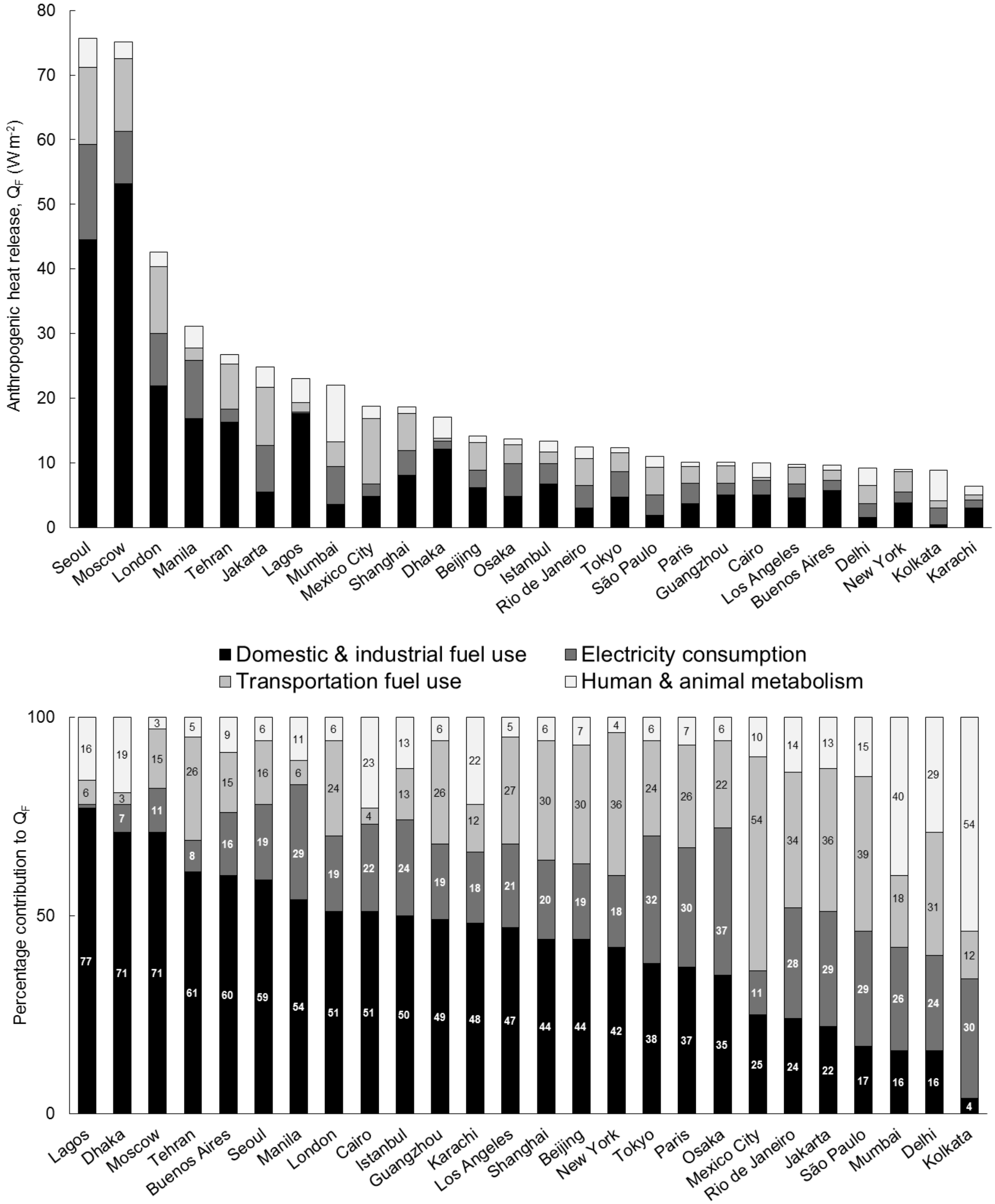

Fig. 2 Sectoral contributions to anthropogenic heat release (Q_F) from megacities in 2011. Top graph = *actual values for urban land area;* bottom graph = *percentage values.*

cold but densely populated cities of Seoul and Moscow, Q_{Fv} accounts for 15 % of total Q_F.

Human and animal metabolism (Q_{Fm}) contributes < 15 % to total Q_F in most megacities, with exceptions in Africa (Cairo, Lagos) and South Asia (Dhaka, Karachi, Mumbai, Kolkata, Delhi) (Fig. 2). Q_{Fm} in lower-density, higher-income megacities like Paris, Tokyo, New York, and Los Angeles accounts for 4–7 % of Q_F, or < 1 W m^{-2}. In Mumbai—the world's most densely populated megacity—heat released from human and animal metabolism represents 40 % of Q_F, or 9 W m^{-2}. This equals heat release from Mumbai's building stock, and exceeds that from its vehicle fleet. Beyond the region, the Q_{Fm} value for Mumbai matches heat release from electricity use in London (8 W m^{-2}), building energy use in Mexico City (7 W m^{-2}), and transportation fuel use in Jakarta (9 W m^{-2}).

4. Discussion

Having sourced our population and energy consumption data from urban metabolism studies not designed for Q_F estimation, we urge our readers to interpret the results carefully and to consider the land area, time period, and population count that each Q_F value represents. The Q_F values for 2011 are spatial averages for large and heterogeneous metropolitan areas, and thus do not convey the microscale patterns and trends inside each city. They do, however, suggest the cultural and physical peculiarities of each megacity that affect anthropogenic heat emissions. The effects of fuel consumption and human metabolism are especially distinct because megacities include some of the richest and poorest places on Earth, and some of its most densely populated.

Overall, Q_F values are largest in megacities with compact forms, wealthy economies, and continental or temperate climates (e.g., Seoul, Moscow, London). Values are smallest in megacities with low population densities (e.g., New York, Los Angeles) or with low-middle income economies in sub/tropical climates (e.g., Delhi, Karachi). In Chinese, Brazilian, and U.S. megacities, ground transportation accounts for more than 30 % of Q_F; in European, African, and South Asian cities, the percentage is significantly smaller. Our most salient finding is that in poor, low-latitude megacities—all of which are densely populated—heat emissions from human and animal metabolism can reach 50 % of total Q_F (e.g., Kolkata). This gives a release of metabolic heat that exceeds that from combustion in other cities. Such result exposes the common—and sometimes unjustified—practice of omitting human and animal metabolism from urban energy balance equations and global climate models.

Our estimates of annual Q_F are consistent with others reported at metropolitan scales for Los Angeles (8 W m^{-2}; SMIC, 1971), London (11 W m^{-2}; Iamarino et al., 2012), Osaka (13 W m^{-2}; Ojima and Moriyama, 1982), and Seoul (55 W m^{-2}; Lee et al., 2009). In megacities where no previous Q_F estimates are reported, our values are a starting point to further investigation. Local researchers will be needed to retrieve high-resolution data on traffic flow, energy consumption, and population density. Efforts to downscale existing values from metropolitan to city level (or from city to local level) might at first follow the prescription of Oke (1987) and Sailor and Lu (2004), such that Q_F increases by a factor of 5–10 with each scale step. Karachi's Q_F of 4 W m^{-2} for the metropolitan area would scale to ~ 20 W m^{-2} for the city proper, and perhaps to ~ 100 W m^{-2} for the core of compact buildings. Q_F values in the Local Climate Zone scheme of Stewart and Oke (2012) can help to guide this process, as can anthropogenic heat flux models highlighting the sensitivity of Q_F to such scaling effects (e.g., Allen et al., 2011). In Greater London, for example, Q_F values increase by a factor of 5 (from 15 to ~ 75 W m^{-2}) when scaled from city (1,000 km^2) to local level (0.1 km^2) (Lindberg et al., 2013).

Our Q_F values relate to those used in regional and global climate models with grid cell size comparable to megacity regions. At this resolution, Q_F values are normally derived from country-level energy consumption data, as in Allen et al. (2011) and Fanner (2009). Using the Community Atmosphere Model with grid resolution ~ 1.4 ° x 1.4 °, Fanner (2009) simulated the effects of Q_F on global climate change. Annual Q_F input values averaged 0.03 W m^{-2} globally, but for individual cells they attained a maximum of 8 W m^{-2} for the megacity of Tokyo. At lower latitudes, Q_F values for megacities were < 3 W m^{-2}. Fanner's simulations show that annual mean temperature change is significant only in cells where Q_F values exceed 3 W m^{-2}, a result that underscores the importance of Q_F in global climate models, and especially in grid cells coinciding with megacity regions. We recommend that Q_F values in such models corroborate with (or originate from) energy consumption data at city or metropolitan scale—rather than at country scale—for the world's biggest cities. This could improve the model's output, partly because Q_F values for megacities of the same country, but of different energy sources and consumption levels, can be differentiated (e.g., Kolkata vs. Mumbai; Tokyo vs. Osaka).

5. Conclusion

Our estimation of metropolitan-level Q_F values in the world's biggest cities demonstrates a first exchange of data between researchers of urban metabolism and urban climate. We encourage the use of such data in urban and global climate models, but only insofar as the original quality and intended uses of those data are observed. Climatologists should be aware of the metabolism data available in cities worldwide, especially for locations where knowledge of the urban atmosphere is least advanced. The results we present here have helped to expand that knowledge through a comprehensive treatment of anthropogenic heat emissions in tropical and mid-latitude environments.

Acknowledgments

Funding for this research was provided by the Enel Foundation.

References

Allen L., Lindberg F., Grimmond C.S.B., 2011: Global to city scale urban anthropogenic heat flux: Model and variability. *Int. J. Climatol.*, **31**, 1990–2005.

Alves M., Matos M., Reichmann M., et al., 2005: Estimation of the dog and cat population in the State of São Paulo. *Rev. Saúde Públ.*, **39**, 891–7.

Eaton H.S., 1877: Presidential address. *Q. J. Roy. Meteor. Soc.,* **III**, 309 ff.

Flanner M.G., 2009: Integrating anthropogenic heat flux with global climate models. *Geophys. Res. Lett.*, **36**, L02801.

Found Animals Foundation, 2009: *Dog and Cat Population Estimates—City of Los Angeles and Los Angeles County* [technical report]. Los Angeles, CA. Retrieved from http://www.foundanimals.org/resources/pet-resources

Garnett A., Bach W., 1965: An estimation of the ratio of artificial heat generation to natural radiation heat in Sheffield. *Mon. Weather. Rev.,* **June**, 383–5.

Hambolu S.E, Dzikwi A.A., Kwaga J.K.P., et al., 2014: Dog ecology and population studies in Lagos State, Nigeria. *Global J. Health Sci.*, **6**, 209–20.

Iamarino M., Beevers S., Grimmond C.S.B., 2012: High-resolution (space, time) anthropogenic heat emissions: London 1970–2025. *Int. J. Climatol.*, **32**, 1754–67.

Ichinose T., Shimodozone K., Hanaki K., 1999: Impact of anthropogenic heat on urban climate in Tokyo. *Atmos. Environ.,* **33**, 3897–3909.

Kennedy C.A., Stewart I.D., Facchini A., et al., 2015: Energy and material flows of megacities. *P. Natl. Acad. Sci. USA*, **112**, 5985–90.

Lee S.H., Song C.K., Baik J.J., et al., 2009: Estimation of anthropogenic heat emission in the Gyeong-In region of Korea. *Theor. Appl. Climatol.,* **96**, 291–303.

Lindberg F., Grimmond C.S.B., Yogeswaran N., et al., 2013: Impact of city changes and weather on anthropogenic heat flux in Europe 1995–2015. *Urban Clim.*, **4**, 1–15.

Ojima T., Moriyama M., 1982: Earth surface balance changes caused by urbanisation. *Energ. Buildings,* **4**, 99–114.

Oke T.R., 1982: The energetic basis of the urban heat island. *Q. J. Roy. Meteor. Soc.,* **108**, 1–24.

Oke T.R., 1987: *Boundary Layer Climates*. Methuen and Co., New York.

Sailor D.J., Lu L., 2004: A top-down methodology for determining diurnal and seasonal anthropogenic heating profiles for urban areas. *Atmos. Environ.,* **38**, 2737–48.

Schlere H., van der Hoek R., 2001: *Livestock Keeping in Urban Areas: A Review of Traditional Technologies Based on Literature and Field* Experiences. FAO Animal and Health Production Paper No. 151. Food and Agriculture Organization (FAO) of the United Nations, Rome.

SMIC, 1971: *Inadvertent Climate Modification: Report of the Study of Man's Impact on Climate (SMIC)*. Massachusetts Institute of Technology Press, Cambridge, MA.

Stewart I.D., Oke T.R., 2012: Local climate zones for urban temperature studies. *B. Am. Meteorol. Soc*., **93**, 1879–1900.

World Health Organization, 2003: *Diet, Nutrition and the Prevention of Chronic Diseases*. WHO Technical Report Series 916. World Health Organization, Geneva.