Anthropogenic Heat Flux in South African Cities: Initial Estimates from the LUCY model

Yerdashin Padayachi*[1] and Tirusha Thambiran[1]

[1] CSIR Natural Resources and the Environment – Climate Studies, Modelling & Environmental Health; P O Box 17001, Congella, 4013, Durban, South Africa

Abstract

The anthropogenic heat fluxes (AHF) from buildings, transport and people are an essential component of the urban climate within cities. Presently limited information on the AHF in South African cities exists. This study quantifies the AHF in South African cities using the LUCY (Large scale Urban Consumption of energy) model. This initial work provides an important baseline to support developing an improved characterisation of urban heat islands under a changing climate in South African cities.

Key words: Urban Climate; Cities; Urban Heat Island; Climate Change

1. Introduction

The anthropogenic heat flux (AHF) modifies local atmospheric circulation and surface temperature within cities (Chen *et al.* 2016). Quantifying the AHF can contribute to a better understanding of the links between urban environments and the local climate in cities through improvements in the parameterisation of the surface energy balance within urban canopy models (UCMs) (Loridan and Grimmond, 2012) that are used to simulate the urban heat island effect within cities. Using the information derived from UCM simulations to inform city-scale climate change policy is key to identifying mitigation measures that have synergies for simultaneously improving a city's resilience to climate change impacts, whilst improving air quality. There is to date, limited information on the AHF in South Africa. In this paper, the LUCY (Large scale Urban Consumption of energY), a global to neighbourhood scale AHF model, is used to estimate the AHF in South African cities. The main objectives of the study include the identification of the main area emission sources of the AHF distinguished by settlement type and the analysis of the mean AHF in the three most populated cities in South Africa. The case studies are used to highlight the need to quantify the AHF in South African cities which is becoming more pronounced due to greater development and urbanisation.

2. Instrumentation and Method

2.1. Background

The LUCY model takes into account waste heat emissions from human metabolism, vehicles and buildings (Eq. 1). When the model calculates the AHF across a geographic area, the spatial resolution of the outputs is 2.5 × 2.5 arc-minutes.

The AHF (Q_F) is calculated:

$$Q_F = Q_m + Q_v + Q_b \qquad (1)$$

Where (Q_m) is the waste heat emissions from human metabolism, (Q_v) is the waste heat emissions from traffic and (Q_b) is the waste heat emissions from buildings. Further information about the data used in the LUCY and the assumptions made in the calculations can be found in Allen *et al.* 2011.

2.2. Applying the LUCY model to South Africa

2.2.1. Parameterising the LUCY model

LUCY was parameterised for South Africa by using country level temperature, population, transport and primary energy consumption data for 2011 (**Table 1**).

Population density data was obtained from the Centre for International Earth Science Information Network (CIESIN) for the year 2010 and 2015. Population density for 2011 was interpolated using the 2010 and 2015 data in ArcGIS 10.3 using the raster calculator tool. Primary energy consumption data were acquired from the Department of Energy (DoE).

Vehicle population data were sourced from the Electronic National Administration Traffic Information System (e-NATIS) database for the

* Tel +27 31 242 2396; Email ypadayachi@csir.co.za

year 2011 and mid-year population data from Statistics South Africa (Stats SA) was used to calculate vehicle density. The vehicle fraction of 0.8 was calculated by dividing the modelled vehicle population from Merven *et al.* (2012) with the live vehicle population statistics from e-NATIS. The modelled vehicle population was assumed to be representative of the actual vehicle population due to the inclusion of scrapping factors and vehicle deterioration rates. Merven *et al.* (2012) determined that the average speed for a private motor vehicle in South Africa was 34 km/h for urban areas. However LUCY only provides pre-selected options for average vehicle speed. An average vehicle speed of 32 km/h was assumed to calculate the AHF across South Africa.

Table 1: Data sources used in this study

Heat Source	Input	Source	Spatial Unit
Metabolic Heat	Population Density	CIESIN	Global 2.5 arc-minute grid
Vehicle heat	Live vehicles population	e-NATIS	South Africa
	Population	Stats SA	South Africa
	Average Vehicle Speed	Merven *et al.* (2012)	South Africa
	Vehicle population modelled	Merven *et al.* (2012)	South Africa
Building heat	Primary energy consumption	DoE	South Africa
	Temperature data	Wilmot and Matsuura (2016)	Global 0.5° × 0.5° grid

2.2.2. Running the LUCY model

LUCY is best suited to provide a rough estimate of the AHF at a global to regional scale (Yang *et al.* 2013). Model runs for the whole year in 2011 were completed and it was found that the day to day variations in the AHF were comparable to the annual mean AHF. Examples are provided for Johannesburg, eThekwini and Cape Town in the results and discussion section. However it was found that LUCY could not readily produce spatial maps of the mean AHF over many days, weeks, months or years. Spatial analysis of the mean AHF in South African cities was an important component of this study in order to identify 'hot-spots' of AHF in the country. Previous studies including Allen *et al.* (2011) and Lindberg and Grimmond (2013) have run the LUCY model for selected days during the year. A similar approach was taken in this study. LUCY was run for two selected days in 2011 with spatial surfaces of the mean AHF produced at a spatial resolution of 2.5 x 2.5 arc minutes as an initial run of the model to provide a first estimate of AHF.

The mean AHF for two days, namely the 17 January 2011 and the 15 August 2011 are presented with August representing normal mean monthly temperatures across South Africa for 2011 and January representing warmer mean monthly temperatures across South Africa for 2011. Mean monthly temperature data was provided by Willmot and Matsuura (2016). The mean monthly temperature for South Africa in August was 17°C and the mean monthly temperature in January was 22°C. LUCY assigns the mean monthly temperature for each day in the month when monthly mean temperature is used instead of mean daily temperature. As such the mean daily temperature data used in the calculations of the AHF by LUCY are equal to the mean monthly temperature

Comparative analysis was used to select the case study cities based on population, total surface area and total primary energy consumption which are the three primary drivers of the AHF (Sailor, 2011). As such the cities of Johannesburg, Cape Town and eThekwini were selected as case studies. Spatial analysis in ARC GIS was done using the zonal statistics tool to determine the spatial mean AHF for 17 January 2011 and 15 August 2011 across different settlement typologies using the Council for Scientific and Industrial Research/South African Cities Network (CSIR/SACN) typology and for the three case study cities used in the study.

3. Results and Discussion

The AHF was compared for both days across the major cities and smaller settlements within South Africa to provide an indication of AHF 'hot spots' (**Table 2**). The mean AHF was found to be greater on the 15 January 2011 compared to the 15 August 2011. The City Region represented by Gauteng has the largest mean AHF in South Africa which is about five times larger relative to other settlement types. Cities in general have a high mean AHF. Population density and energy consumption per land use type are likely drivers in the spatial distribution of the AHF (Sailor, 2011) across South Africa.

In **Table 3**, the high population, total surface area and total primary energy consumption contributed by different land use activities within the major cities in South Africa are compared. Total surface area, population and total primary energy consumption are not always proportional, for example Tshwane is quite large in area, has a large population but the city's energy consumption is much lower than that of Cape Town. Cape Town, eThekwini and Johannesburg have the largest populations in South Africa.

Table 2: The mean AHF by settlement type for South Africa for 17 January 2011 and 15 August 2011.

Settlement type	AHF mean for 17 January 2011 ($W.m^{-2}$)	AHF mean for 15 August 2011 ($W.m^{-2}$)
Sparse Rural	0.03±0.21	0.02±0.18
Service Town	0.68±1.13	0.60±0.99
Dense Rural	0.27±0.24	0.24±0.21
High Density Rural	0.34±0.44	0.30±0.38
Local or Niche Town	0.27±0.53	0.24±0.46
Regional Centre 2	1.16±2.09	1.04±1.86
Regional Centre 1	1.22±2.27	1.06±1.95
City	1.30±2.65	1.13±2.29
Regional Centre 3	1.02±2.21	0.89±1.94
City Region	3.25±6.46	2.83±5.63
Homeland	0.03±0.05	0.03±0.05
Non-Homeland	0.00±0.00	0.00±0.00

The City of Johannesburg has the greatest mean AHF relative to eThekwini and Cape Town which is about 6.9 $W.m^{-2}$ on 17 January and 6.3 $W.m^{-2}$ on 15 August (**Table 4**). The mean annual AHF is provided for comparability. While the mean AHF on both days are within the deviations of the mean annual AHF, the mean AHF on 17 January is larger, relative to the mean AHF on 15 August. The results do indicate that the AHF mean on a 'hot day' is higher relative to a 'normal day'.

Table 3: Population, total surface area and primary energy consumption of South African metropolitan municipalities in 2011.

City	Population[1] (million)	Total Area[2] (km^2)	Primary Energy Consumption[3] (PJ)
Cape Town	3.74	816	159
eThekwini	3.42	1062	210
Johannesburg	4.40	1645	176
Mangaung	0.74	176	15
Buffalo City	0.76	168	23
Nelson Mandela Bay	1.16	389	31
Tshwane	2.91	1230	93
Ekurhuleni	3.17	1975	127

1. Data source: Stats SA; 2. Data source: Municipal Demarcation Board; 3. Data source: Sustainable Energy Africa (SEA, 2015)

When the mean AHF in Johannesburg for 2011 is compared to other cities (**Table 5**), the AHF in Johannesburg is shown to be significantly smaller due to the city's relatively smaller population. The mean AHF in London, for example, is almost twice that of Johannesburg with a population two times larger than Johannesburg.

Table 4: The mean AHF for Johannesburg, eThekwini and Cape Town on 17 January 2011 and 15 August 2011.

City	Annual AHF mean ($W.m^{-2}$)	AHF mean for 17 January 2011 ($W.m^{-2}$)	AHF mean for 15 August 2011 ($W.m^{-2}$)
Johannesburg	4.52±7.87	6.92±9.93	6.34±8.98
eThekwini	3.40±5.93	4.23±7.25	3.67±6.23
Cape Town	2.65±4.92	3.24±6.57	2.70±5.51

Table 5: Comparitive analysis of AHF mean for different cities

City	Population (millions)	Total Area (km^2)	Year of estimate	AHF Mean	Citation
Johannesburg	4.4	1645	2011	4.5	This study
Beijing	19.61	3937	2010	17	Yang *et al.* (2014)
Shanghai	23.02	3885	2010	19	Yang *et al.* (2014)
Guangzhou	12.7	3820	2010	7.8	Yang *et al.* (2014)
Taiwan	23.20	1140	2010	9.6	Koralegedara a *et al.* (2016)
London	7.56	1738	2005-2008	10.9	Iamarino *et al.* (2012)
Sao Paul	10.89	2707	2007	13.2	Ferreira *et al.* (2011)

By 2030, the UN population division predicts that Johannesburg will be one of six megacities in Africa. The production of waste heat may not be a problem at present while energy consumption levels remain relatively low. However, accelerated population growth and energy consumption in the future will contribute to greater waste heat production. The effect of the AHF on urban temperature will become even more pronounced in the future. This will be additional to the climate change impacts on warming patterns in the city.

Conclusions

The LUCY model has been used in this study to provide an initial estimate of the AHF in South African settlements. The results indicate that cities in South Africa are important sources of waste heat emissions. The inclusion of the comparison between the AHF mean on a 'hot day' versus a 'normal day' highlights the sensitivity of the AHF to temperature change. Waste heat emissions in cities contribute to increasing urban temperatures and in turn higher urban temperatures contribute to increasing waste heat production. Waste heat is an unwanted product of energy consumption and under future scenarios of development and climate change in South African cities, the AHF within South African cities will grow. The AHF will contribute much more too urban temperature change in the future As a consequence, waste heat emissions will become an important trade-off for cities to account for in climate change policy.

AHF is an essential factor in city-scale atmospheric circulation and surface temperature and as such, there is a need to improve our ability to quantify the AHF in South African cities. Future work towards improving the parameterisation of building, transport and human sources of waste heat emissions within these cities is envisaged. The input of such data into UCMs will help support research into urban heat island effects in South African cities under a changing climate.

References

Allen, L., Lindberg, F., & Grimmond, C. S. B. (2011). Global to city scale urban anthropogenic heat flux: model and variability. *International Journal of Climatology*, 31(13), 1990-2005.

Chen, B., Dong, L., Liu, X., Shi, G. Y., Chen, L., Nakajima, T., & Habib, A. (2016). Exploring the possible effect of anthropogenic heat release due to global energy consumption upon global climate: a climate model study. *International Journal of Climatology*.

Ferreira, M. J., de Oliveira, A. P., & Soares, J. (2011). Anthropogenic heat in the city of São Paulo, Brazil. *Theoretical and applied climatology*, *104*(1-2), 43-56.

Iamarino, M., Beevers, S., & Grimmond, C. S. B. (2012). High-resolution (space, time) anthropogenic heat emissions: London 1970–2025. *International Journal of Climatology*, *32*(11), 1754-1767.

Lindberg, F., Grimmond, C. S. B., Yogeswaran, N., Kotthaus, S., & Allen, L. (2013). Impact of city changes and weather on anthropogenic heat flux in Europe 1995–2015. Urban Climate, 4, 1-15.

Loridan, T., & Grimmond, C. S. B. (2012). Characterization of energy flux partitioning in urban environments: links with surface seasonal properties. *Journal of Applied Meteorology and Climatology*, 51(2), 219-241.

Merven, B., Stone, A., Hughes, A., & Cohen, B. (2012). Quantifying the energy needs of the transport sector for South Africa: A bottom-up model. University of Cape Town, Cape Town, RSA.

Koralegedara, S. B., Lin, C. Y., Sheng, Y. F., & Kuo, C. H. (2016). Estimation of anthropogenic heat emissions in urban Taiwan and their spatial patterns. *Environmental Pollution*, 215, 84-95.

Kušnerová, M., Valíček, J., Harničárová, M., & Tozan, H. (2016). Prediction of Optimal Load and Performance of Thermal Batteries. In *Applied Mechanics and Materials* (Vol. 821, pp. 641-648). Trans Tech Publications.

Sailor, D. J. (2011). A review of methods for estimating anthropogenic heat and moisture emissions in the urban environment. *International Journal of Climatology*, 31(2), 189-199.

Sustainable Energy Africa (2015). State of Energy in South African Cities 2015, Sustainable Energy Africa, Cape Town, RSA.

Willmott, C. J. and K. Matsuura (2016) Terrestrial Air Temperature: 1900-2014 Gridded Monthly Time Series, Retrieved from http://climate.geog.udel.edu/~climate/html_pages/Global2014/README.GlobalTsT2014.html. Accessed 02 April 2016.

Yang, Y., Endreny, T. A., & Nowak, D. J. (2013). A physically based analytical spatial air temperature and humidity model. *Journal of Geophysical Research: Atmospheres*, 118(18).

Yang, W., Chen, B., & Cui, X. (2014). High-resolution mapping of anthropogenic heat in China from 1992 to 2010. *International journal of environmental research and public health*, *11*(4), 4066-4077.