Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 198 (2017) 589 – 599

Procedia Engineering

www.elsevier.com/locate/procedia

A sensitivity study relating to neighbourhood-scale fast local urban climate modelling within the built environment

Yasemin Didem AKTAS[a,*], Jenny STOCKER[b], David CARRUTHERS[b], Julian HUNT[c]

[a]UCL Department of Civil, Environmental and Geomatic Engineering, Epicentre Research Group, Gower Street, London WC1E 6BT, UK
[b]Cambridge Environmental Research Consultants (CERC), 3 King's Parade, Cambridge CB2 1S
[c]UCL Department of Earth Sciences, Gower Street, London WC1E 6BT, UK

Abstract

The rapid increase in urban populations during the last century, together with the threat of climate change has motivated research focusing on the impact of land-use on urban climates. High-resolution neighbourhood-scale modelling tools developed to account for the complex three-dimensional surfaces and volumes within an urban area are able to predict temperature perturbations over an urban domain with reference to varying land-use. However, land-use classes chosen to model the urban landscape often reflect the function, rather than the material, and hence overlook different building materials that compose the built environment.

The purpose of this study is to demonstrate that for a robust appraisal of local climate variations, it is important to use representative land-use parameters that account for materials that form the urban landscape, instead of functions. The response of a high-resolution local climate model to an improved parameterization of the built environment is investigated using the local-scale urban climate modelling tool, ADMS-Urban. In this study, a more elaborate set of land-use classes is collated which distinguishes between different building materials that have varying thermal parameters. A novel approach to calculating the thermal admittance is proposed, reflecting different building materials used for the building facades and the roofs.

This study demonstrates that refining model input parameters to correctly represent various construction materials used within the urban tissue, as well as the proposed, advanced method for calculating thermal admittance leads to significant temperature differences compared to when broad assumptions are used, especially under low wind conditions common in equatorial cities.

Keywords: land-use, urban heat island, ADMS-Urban, thermal admittance, albedo, surface resistance to evaporation

---

1. Introduction

Extreme heat events in urban areas can cause serious health problems, including cardiovascular or respiratory problems that can lead to strokes and even premature mortality (Hoshiko et al., 2010; O'Neill and Ebi, 2009), especially in women (Hajat et al., 2007) above 65 years of age (Huynen et al., 2001), while future projections show that the mortality rate can drastically rise with increasing global temperatures (Hajat et al., 2014). Overheating of cities also increases the anthropogenic forcing to the environment with increasing energy demand for cooling purposes, which further exacerbates the urban heat island due to the additional waste heat output by AC systems (Salamanca et al., 2014). As local urban warming is coupled to global warming, which is considered mainly greenhouse gas-induced, heat waves and associated problems constitute environmental hazards frequently observed within highly urbanized areas (Hunt et al., 2017). Whilst temperature monitors deployed in locations throughout a city can be useful to have an understanding of urban heating, it is important to evaluate and quantify the vulnerabilities of an urban domain to heat-induced risks by means of urban climate models primarily in order to (1) accurately assess the impact of current and future urban planning strategies, (2) gain insight into the future projections for energy demand, and (3) appraise potential health problems.

Urban climate modelling can be performed at a range of spatial scales. Mesoscale meteorological model such as WRF (Skamarock et al., 2008) and the UK Met Office Unified Model (Bohnenstengel et al. 2011) include modules that account for the build-up of the urban heat islands on the city scale whereas neighbourhood-scale models such as ADMS (Virk et al., 2015) are able to resolve local temperature variations at street level that relate to, for instance, the distribution of green space within the urban landscape. In contrast to the mesoscale models, local-scale models are able to perform fast simulations of a series of land-use scenarios; these tools have been widely used in the last decade or so to further understand the temperature perturbations due to land use in urban domains (Hamilton et al., 2014), and hence can be used to identify risk areas and appraise the severity of future problems relating to urbanization and climate change (Virk et al., 2014).

This study considers how refinements to urban climate model inputs alter model predictions, specifically those values that define the capacity of the various materials that form the urban landscape to absorb/reflect, store and reradiate energy. We

---

[*] Corresponding author. Tel.: +44 2076 791 566, *E-mail address:* y.aktas@ucl.ac.uk

Peer-review under responsibility of the organizing committee of the Urban Transitions Conference
doi:10.1016/j.proeng.2017.07.113

pose and discuss three questions that relate to how the land use parametrization can be improved. The findings of this work are then discussed within the context of health implications; future work requirements are presented.

Nomenclature

TA_{eff}	effective thermal admittance
A_g	ground area
ΣA_r	total roof area within a grid
ΣA_b	total building façade area within a grid
TA_g	ground thermal admittance
TA_r	roof thermal admittance
TA_b	building thermal admittance
λ_f	frontal density
λ_p	planar density
V_{be}	volume of the building envelope
V_b	volume of the building

2. The input parametrization: is there space for development?

ADMS-Urban is a fast, neighbourhood-scale modelling tool that calculates land-use related temperature perturbations relative to upwind meteorological conditions. The model uses morphological and meteorological input parameters, along with inputs that define the differing thermal properties of materials within the urban domain; the morphological parameters include normalized building volume and the surface roughness parameter, and the upwind meteorological data include wind speed and direction, air temperature, specific humidity, latent heat flux and ground heat flux. Input parameters are also required that define the capacity of various urban building materials to absorb, store and reradiate heat, for instance albedo, surface resistance to evaporation and thermal admittance parameters; it is the refinement of these land-use parameters, which is the primary focus of this study. Albedo is the measure of the reflectivity of a surface. Using more reflective, i.e. high albedo materials, is commonly recommended in urban planning to mitigate urban heating (Touchaei et al., 2016), and has led to the 'reinvention' of cool roofs that was shown to be effective in limiting urban overheating under strong solar radiation (Virk et al., 2014; Jacobson and ten Hoeve, 2012). The surface resistance to evaporation parameter defines the resistance of a material to evapotranspiration. Lastly, thermal admittance is a measure of the capacity of a surface to absorb heat. This study considers how refining these input land-use parameters leads to methods for ameliorating our capacity to represent the impact of land use on urban climate and simulate the urban heat island.

ADMS-Urban (Owen et al., 2000) is a street-scale urban environmental modelling system originally developed to predict air pollution within cities and agglomerations. During the LUCID project (Mavrogianni et al. 2011) the ADMS system was modified to allow the calculation of a spatially varying temperature and humidity field, using theory based on Carruthers and Weng (1992). The model requires as input spatially varying data that relates to surface properties (albedo, thermal admittance, surface resistance to evaporation, normalized building volume and surface roughness) in addition to hourly meteorological data that are representative of upwind conditions; these may be measured meteorological data or else values derived from output from a mesoscale model.

The current study follows from earlier work undertaken by Hamilton et al. (2014), where ADMS was used to investigate the impact of land use on temperature for three different land-use scenarios in London's Olympic parkland (Figure 1); that paper reaches conclusions relating to the built environment and amount of vegetation. The current study focuses on the same area but uses a considerably further developed version of the model to explore how input parameters can be amended to improve modelling practice. The results obtained for various model inputs modified in line with each of questions posed in the following sections are compared and presented against those obtained for a 2012 Olympic Parkland *base case*, i.e. using conventional methods for deriving land-use databases.

Figure 1: Google Earth view of Olympic Parkland (blue area shows the output domain)

2.1. Question 1: Can a meaningful difference in the calculated temperature variations be obtained using a material-based land use categorization?

Conventional modelling practices usually use the existing generic, function-based land use categories that have been designed to understand how much of land falls in each of four main land use types, i.e. forest, agricultural, residential and industrial, for regulation of land use and tax management purposes (Anderson et al., 1976). The UK's Generalised Land Use Database (GLUD) given in Table 1 is an example of such land use categorization systems; this categorization was developed "to meet immediate needs for comparable land use statistics on residential building density and urban green space at the regional, local and neighbourhood level" (Harrison, 2006). It is clear that the GLUD classifications are defined in terms of usage (for instance domestic, non-domestic or communal use) and consequently the categories reflect function rather than material properties; this is in conflict to the requirements for urban climate modelling, which require material information. Thus in many cases, the specification of land use data collated for regulatory purposes is incompatible with that required for urban climate modelling. As urban climate modellers are often required to make use of the regulatory data, climate modelling of an urban domain is hindered because the land use categories are vague, or irrelevant, for instance, the distinction between domestic and non-domestic buildings.

Table 1: Generalised land use database (GLUD) categories and corresponding albedo, surface resistance to evaporation and thermal admittance values (after Hamilton et al., 2014).

Generalised land use database (GLUD) categories	Albedo (-)	Surface resistance to evaporation (s m^{-1})	Thermal admittance (J m^{-2} $s^{-1/2}$ K^{-1})
Unclassified	0.05	200	1205
Water	0.08	0	1545
Domestic buildings	0.12	200	1505
Non-domestic buildings	0.12	200	1505
Roads	0.08	200	1205
Paths	0.08	200	1096
Rail	0.08	200	1150
Green space	0.16	100	300 (Oke, 1988)
Domestic gardens	0.19	60	300 (Kaul, 1988)
Other (mainly hardstanding)	0.05	200	1205

Albedo, surface resistance to evaporation and thermal admittance values can be assigned to each GLUD category; Table 1 presents values taken from Hamilton et al. (2014), except for the thermal admittance values for green space and domestic gardens categories, as these values are reported significantly differently in the relevant literature. Albedo is defined as the ratio of reflected shortwave solar radiation to the incident solar radiation and as such varies between 0 and 1 (CERC, 2015); surface resistance to evaporation is a reverse measure of the availability of surface wetness; and thermal admittance is a measure of a volume's capacity to store and re-radiate heat. As the total albedo, surface resistance to evaporation and thermal admittance of a particular domain is a function of the components forming the domain and its morphology, each grid point within the model domain takes one GLUD class, which is based on the predominant features in the vicinity of that location; thus each grid point may be assigned values of albedo, surface resistance and thermal admittance value, as shown in Table 1.

For the current study, in order to assess model sensitivity to the land-use parameters, a selection of the GLUD categories were revised to reflect building *materials* rather than *function* (Table 2). The corresponding albedo, surface resistance to evaporation and thermal admittance values were amended where information was available from the literature. Land-use survey data were refined by undertaking a small-scale, virtual survey in the urban domain using Google Earth Street View; a distinction was made between concrete and masonry buildings, in addition to the revision of other categories. For instance, the 'paths' category was changed to 'dry bare soil', and 'green spaces' and 'domestic gardens' were re-categorized as 'woods' and 'grass', as appropriate. The generic values for domestic and non-domestic buildings (Table 1) were applied to concrete buildings as these were in the ranges reported for concrete in the literature. Other parameter values for the new categories were selected from the literature (Table 2). Importantly, while concrete is a rather impermeable building material, this is not the case for porous masonry, which has been shown to absorb and release significant amounts of moisture depending on the outdoors weather conditions (D'Ayala and Aktas, 2016; Aktas et al., 2015); therefore the surface resistance to evaporation should be lower. The literature on this however is extremely sparse, and in this exploratory study a slightly reduced value, 180, was used for masonry, considering that the difference between evapotranspiration capacities of concrete and masonry would not be very high on a dry, mid-summer day – this value needs to be fine-tuned in future validation studies.

The *base case* and amended land use distributions over the model domain are shown in Figure 2. It should be noted that the area toward the north of the site 'Eton Manor Transport hub' that was used for parking during the Olympics was classified as 'road', whereas in reality it is green space. This is not an issue as the aim here is to explore the differences in the calculated temperature values with other systematic revisions in the land-use, rather than to validate the models.

Table 2: Extended land use categories and corresponding albedo, surface resistance to evaporation and thermal admittance values

Extended land use categories	Albedo (-)	Surface resistance to evaporation (s m^{-1})	Thermal admittance (J m^{-2} $s^{-1/2}$ K^{-1})
Unclassified	0.05	200	1205
Water	0.08	0	1545
Concrete buildings	0.12	200	1505
Masonry buildings	0.35 (Bretz et al., 1992)	180*	1070 (Oke, 1988)
Roads	0.08	200	1205
Bare soil (assume dry)	0.20 (Ojima and Toriyama, 1982)	150	600 (Oke, 1987)
Rail	0.08	200	1150
Woods	0.15 (Ojima and Toriyama, 1982; Taha et al., 1988)	100 (Oke, 1987)	300
Grass	0.20 (Stull, 1988)	70 (Oke, 1988)	300
Other (mainly hardstanding)	0.05	200	1205

* as the literature does not offer a surface resistance to evaporation value for brick masonry, that of concrete was reduced to 180 to reflect the relatively porous and absorptive nature of brick compared to almost impervious concrete.

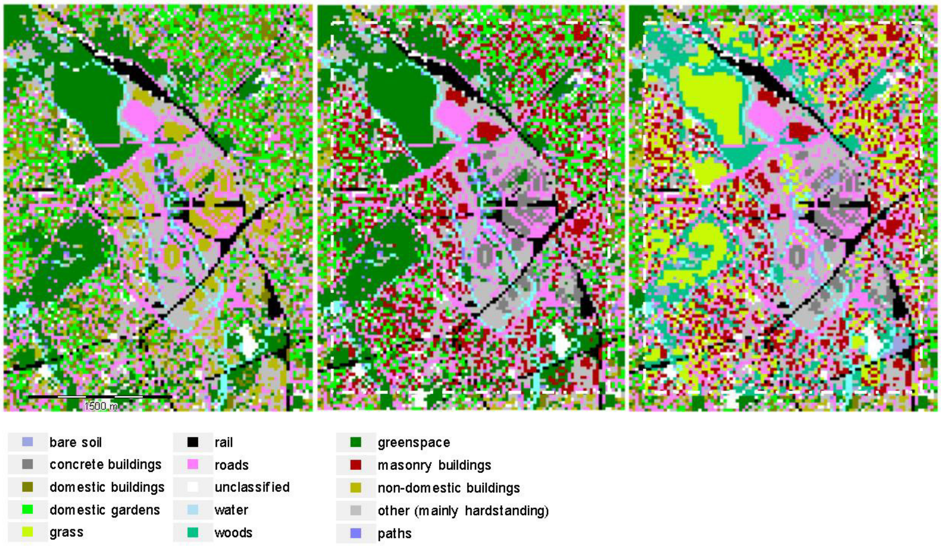

Figure 2: Land use distribution over the input domain for (a) GLUD categories (*base case*), (b) masonry and concrete buildings, instead of domestic and non-domestic buildings (*case#1*) and (c) extended land use categorization given in Table 2 (*case#2*).

The *base case* 2012 Olympic Parkland distribution of land use broadly corresponds to that used in Hamilton et al. (2014); differences relate to the land use data being revised to more accurately reflect the current condition of Olympic Parkland, as the original modelling work was based on development plans for the site, when the ADMS model was used for temperature forecasting during the 2012 Olympic Games period, as part of London's *air*TEXT forecasting system (Stidworthy et al., 2013). These *base case* GLUD classes (Figure 2a) were amended, firstly to differentiate between concrete and masonry buildings (case#1) (Figure 2b) and then comprehensively revised in line with the categorization given in Table 2 (case#2) (Figure 2c). Note that whilst amending the classes, it was necessary to keep the thermal classifications consistent with the *base case* within a ~ 200 m wide domain border; this restriction ensures that all configurations are subject to the same upwind meteorological conditions and therefore that the results obtained from different scenarios are directly comparable.

Temperature scales in Figure 3&5-7 were kept different in order to show distribution of the calculated temperature perturbations with the highest resolution possible.

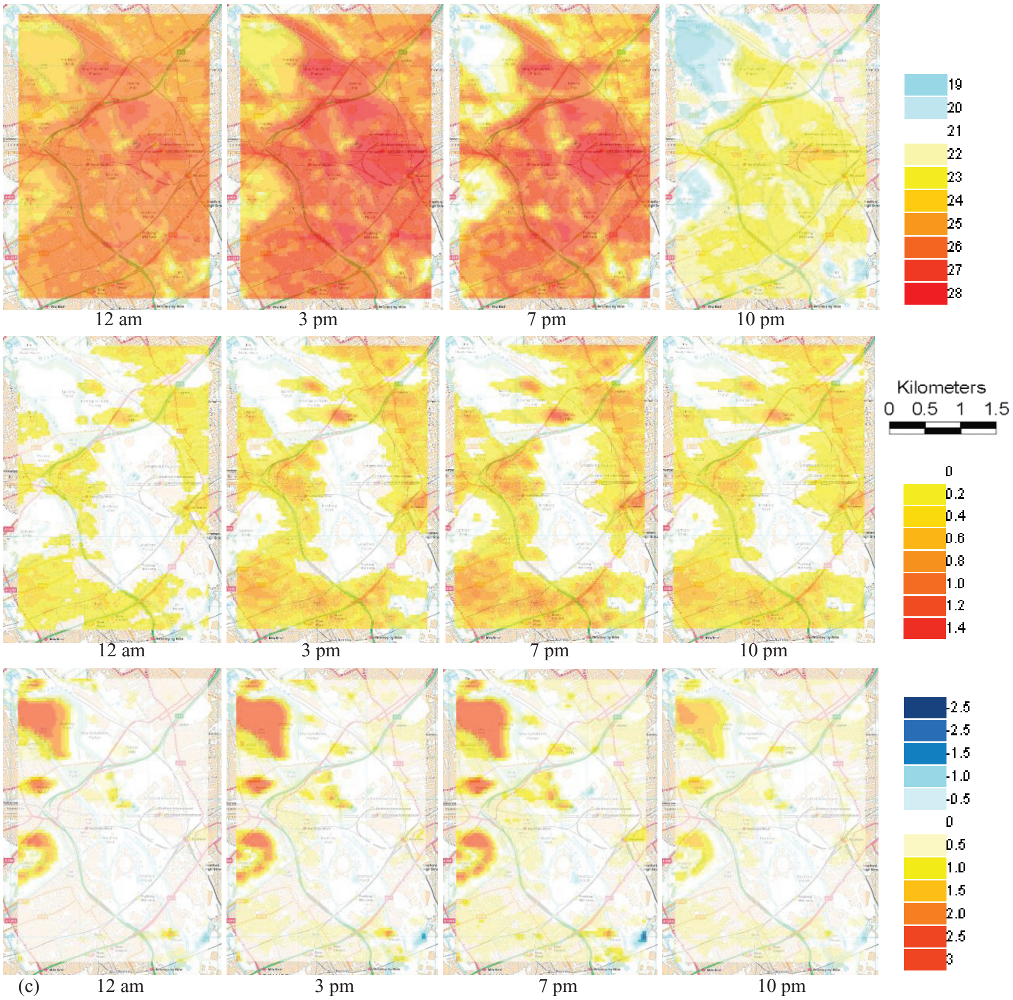

Figure 3: (a) Calculated absolute temperature distribution over the modelling domain for indicated times of a typical summer day for GLUD categories (*base case*), (b) differences obtained when building categories are changed as concrete and masonry (*base case* – case#1), and (c) when the entire land use categorization is amended as shown in Table 2 (*base case* – case#2).

* Please note that temperature values reported here might differ from those originally reported by Hamilton et al. (2014) because of modifications that took place in the land use within the area in the course of last 2 years, as well as some amendments made in the ADMS software.

As seen from Figure 3(a), whilst the upwind temperatures on a typical summer day between 12 am and 10 pm as shown in the plots above vary between around 19°C and 28°C, allowing for the spatial distribution of temperature leads to much greater variations over the urban domain: 19°C to 24°C on the Hackney Marsh grassland area and 23°C to 28°C in the built-up central location. By differentiating between concrete and masonry structures (case#1) (Figure 3b), we see that the temperature values on Hackney Marsh and other green areas do not change, however the predicted temperatures in the built-up section surrounding the central concrete area decrease by up to 1.4°C. This is because the thermal admittance value assigned to a significant part of the built environment is reduced as it is made of masonry, and therefore it absorbs and re-radiates heat less easily. When the land use categories are amended more extensively and the thermal parameters assigned to each category are modified as given in Table 2 (case#2), the temperature distribution changes by up to 3°C (Figure 3c); in this case, differences in calculated temperature perturbations over green areas are due to changes in the assigned albedo and surface resistance to evaporation values (Tables 1&2).

2.2. Question 2: Can we find a way to consider both the materials used for the building facades and the roofing to calculate an effective thermal admittance value?

Heat absorption and storage capacity of buildings is conventionally expressed by means of a single value; however, the buildings are formed by a combination of different materials. This study proposes a novel way of calculating thermal admittance value for each grid with one or multiple buildings such as Figure 4. By using the standard formulations for non-dimensional building frontal and planar areas, λ_f and λ_p, respectively (Grimmond and Oke, 1999) given in Eqs. 1-2 together with the assumption that the total building planar area is equal to the total roof area in a grid (Eq 3), it is straightforward to calculate (Eq 4) a weighted average effective thermal admittance value (TA_{eff}) that accounts for: building volume; thermal admittance of the building facades (TA_b) and roof materials (TA_r); and the thermal admittance of the ground (TA_g). This equation accounts for two of the building(s) facades) receiving solar radiation, as well as the total area of the roof(s) and the ground surrounding the buildings. In these calculations TA_g and TA_r were taken as 1205 and 1070 J m^{-2} s$^{-1/2}$ K^{-1} respectively and the calculations resulted in the thermal admittance values assigned to grids with buildings in the range 1088 to 1505 J m^{-2} s$^{-1/2}$ K^{-1}. Thus by accounting for the 3D nature of buildings and the variation of building materials (case#3), the resultant thermal admittance is more varied relative to the single value originally used for concrete buildings (1505 J m^{-2} s$^{-1/2}$ K^{-1}) and for masonry buildings (1070 J m^{-2} s$^{-1/2}$ K^{-1}), as shown in Figure 5a.

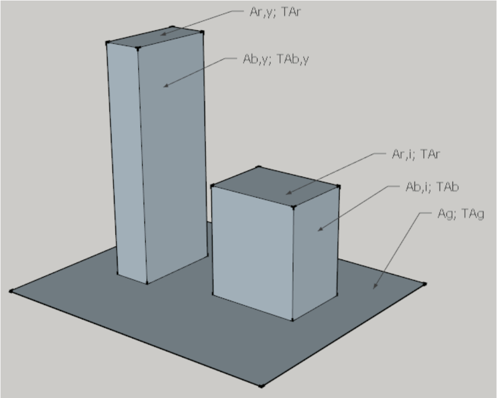

Figure 4: A typical grid with buildings

$$\lambda_f = \frac{\Sigma A_b}{A_g},\ \lambda_p = \frac{\Sigma A_p}{A_g},\ \Sigma A_r = \Sigma A_p \qquad (1\text{-}3)$$

$$TA_{eff} = \frac{A_g - \Sigma A_r}{A_g} TA_g + \frac{\Sigma A_r}{A_g}\left(\frac{\Sigma A_r TA_r + 2\Sigma A_b TA_b}{\Sigma A_r + 2\Sigma A_b}\right) = (1-\lambda_p) TA_g + \lambda_p \frac{\lambda_p TA_r + 2\lambda_f TA_b}{\lambda_p + 2\lambda_f} \qquad (4)$$

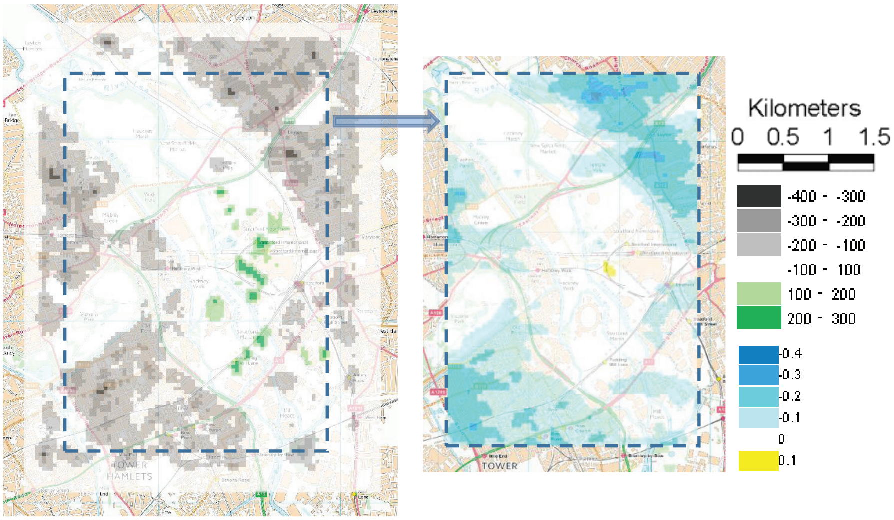

Figure 5: (a) The difference in thermal admittance input values and (b) the difference in the temperature values obtained over the model domain for the extended land use categorization given in Table 2 (the results for which are reported in Figure 2c) and those calculated using Eq 4 (case#2-case#3).

Figure 5b shows the difference in predicted temperature values obtained using the standard thermal admittance values (case#2) and those derived using Eq. 4 (case#3) at 7 pm. Temperature differences up to around 0.4°C, mostly in the masonry area surrounding the central built-up concrete area, are observed. This is because in this area, the effective thermal admittance values assigned to this area have in general increased, which leads to increased absorption of heat into the ground at this time of day – hence negative difference values in the calculated temperature perturbations. The effective thermal admittance of the mainly concrete area, on the other hand, decreases due to lower thermal admittance of the roof.

2.3. Question 3: Does the entire building volume actually contribute heat absorption and storage? If not, would this create a meaningful difference in the calculated temperature variations?

Heat absorption, storage and re-radiation is a volumetric phenomenon. However, in the current ADMS–Urban formulation, the thermal admittance parameter is defined per unit area i.e. no account is taken of the building volume; further, building materials are assumed homogeneous. In reality, buildings consist of an outer layer (a shell), with an internal space containing air separated by partition walls, slabs and so on. The impact of the heterogeneous nature of buildings on the calculated temperature perturbations has been investigated by including the ratio of volume of the building envelope (as a shell) to volume of the building (as a cuboid) in the equation below (Eq 5). When the V_{be}/V_b ratio is equal to 1, 100% of the building volume contributes to the heat absorption and storage process. The V_{be}/V_b ratio however can be changed to model buildings with different levels of contribution to the heat absorption and storage. The previous cases considered correspond to the V_{be}/V_b ratio equal to 100%; V_{be}/V_b ratio equal to 25%, 50% and 75% were also modelled (case#4).

$$TA_{eff} = (1-\lambda_p)TA_g + \lambda_p \frac{\lambda_p TA_r + 2\lambda_f TA_b}{\lambda_p + 2\lambda_f}(V_{be}/V_b) \tag{5}$$

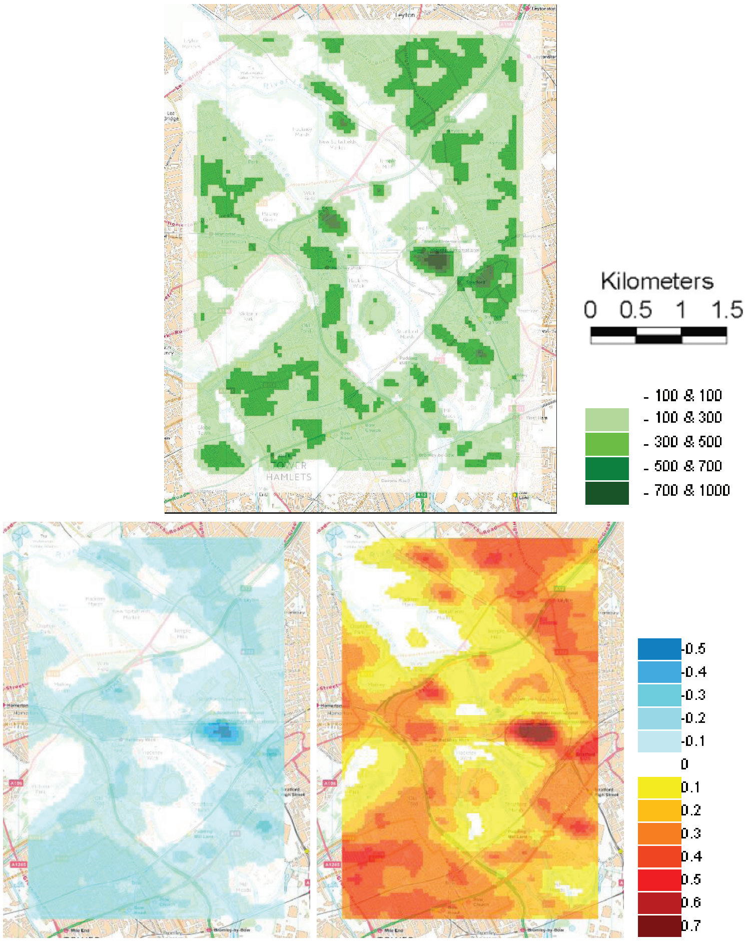

Figure 6: (above) The difference in thermal admittance input values and (below) the difference in the temperature values over the model domain obtained for 3 and 7 pm for the calculated thermal admittance values with V_{be}/V_b ratio equal to 25% and 100% (case#3-case#4)

Figure 6 shows that the differences in thermal admittance values calculated for V_{be}/V_b ratio equal to 100% and 25% - the calculated difference is up to 0.7°C. The differences are most pronounced at the Stratford International Train Station, as this is essentially a large, empty building where the thermal capacity of the inner volume is important.

The magnitude of all temperature perturbations calculated in this study will further increase in low-wind speed atmospheric conditions common in tropical cities. In order to demonstrate the influence of wind speed on the predicted temperature values, the wind speed for the typical UK summer day was reduced from 1.8 m/s to 0.9 m/s. The difference in the calculated temperature perturbations is now up to 1.6°C (Figure 7).

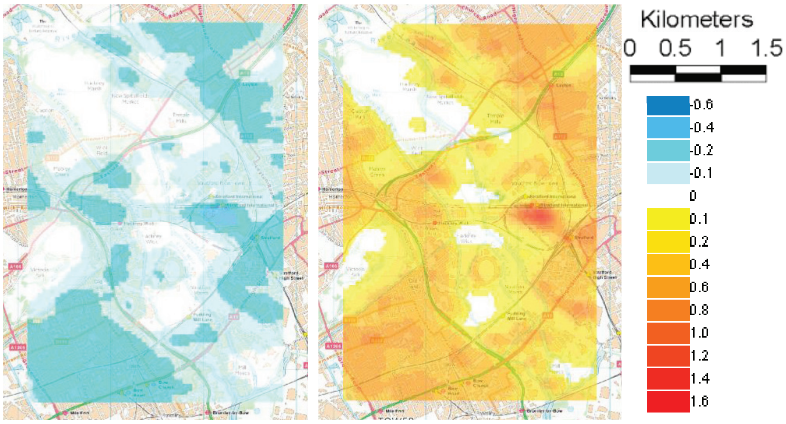

Figure 7: The difference in the temperature values obtained for 3 and 7 pm for the calculated thermal admittance values with V_{be}/V_b ratio equal to 100% and 25% for halved wind speed values (case#3-case#4 for halved wind speed values)

3. Discussion and future work

This study explores the sensitivity of the neighbourhood-scale urban climate model, ADMS-Urban, to a range of inputs that have been refined so as to better represent 'land material' as opposed to 'land use'. Specifically, differentiating between different building materials and refining thermal admittance values leads to significant changes in the predicted temperatures. Consequently, for each urban domain it is important to select a meaningful set of land use/material categories, in particular if the results obtained are to be used to evaluate the health implications of urban heating. Recently, Heaviside et al. (2016) and Buchin et al. (2016) estimated that even a 1°C increase in the daily mean temperatures would double the expected heat-related mortality. Further, the majority of urban climate modelling studies focus on relatively local areas; consequently, it is recommended to undertake detailed surveys for such areas, despite the associated cost overhead. All other refinements demonstrated in this paper, such as recalculating thermal admittance to account for the differing properties of the building roofs and facades, and building envelopes, can be performed easily using widely available spreadsheet programs. However, in order to have confidence in the model predictions, it is important that future work includes comprehensive validation of the temperature field predicted by the model.

Future work also includes refining the albedo and surface resistance to evaporation parameters on the basis of time of the day, colour, texture and level of preservation of the surfaces that form the urban landscape. It is known that light-coloured surfaces reflect more than dark-coloured surfaces, therefore the albedo of the non-plastered, dark coloured façade of a brick masonry structure (or stained surfaces of an aged concrete building) will have different reflectivity properties than a brick masonry structure with whitewashed or painted surfaces in light colours (or a fresh, lightly coloured concrete surface). Further, the extensive use of glass on high-rise building facades within the central business districts of modern cities impacts on the resultant urban albedo, and whilst concrete surfaces are relatively impermeable, masonry is able to absorb large amounts of moisture, thus reducing surface resistance to evaporation. While this field of research is mainly dominated by the agricultural and urban vegetation research, further experimental work is urgently needed to evaluate evapotranspiration capacities of porous building materials. Other factors that might decrease surface resistance to evaporation include aging, poor maintenance etc.

Another important point is that V_{be}/V_b ratio is dependent on wall thickness, which can be generally quite different in concrete and masonry buildings. This, along with other refinement and validation with regards to the V_{be}/V_b ratio, should be further explored by future studies.

Finally, the thermal admittance of saturated soil can increase by up to five times relative to the value of unsaturated soil, which has a significant impact on the temperature variations in suburban landscapes and parkland areas. Planned future work therefore also includes the integration of precipitation events and the subsequent cooling effect into the local urban climate model ADMS-Urban; this is particularly relevant for application of the model in tropical climates.

4. Conclusions

This exploratory study clearly demonstrates the need for improvements in the input data used by fast, neighbourhood scale urban climate modelling tools such as ADMS-Urban. Although using the readily available land-use categories is the most straightforward approach to deriving model inputs, the results reported in this paper show that more detailed surveying is worthwhile in order to establish a reliable parametrization. Further sensitivity analyses are needed in order to draw robust conclusions regarding redundancy in model inputs and validation of the model predictions against measurements is a necessary next step.

Validation studies are planned in near future as part of the Future Cities project titled “Disaster Resilient Cities: Forecasting Local Level Climate Extremes and Physical Hazards for Kuala Lumpur”. During validation anthropogenic heating due to traffic and air conditioning systems will also be integrated into the model, and the accuracy of model predictions will be shown in comparison to observed temperature data in order to identify threshold criteria required to produce realistic urban climate predictions. Following this example of best practice, the existing modelling tools can reliably be used for the simulation of complex future scenarios and for a robust assessment of the relevant health implications.

Acknowledgements

This study has been supported by the project titled “Future Cities: Science to Action for Building Resilience of Urban Communities to Climate Induced Physical Hazards” funded by Newton Ungku Omar Funds, and was presented in the 5th ANCST Workshop on Climate Change and Disaster Resilience – Post Sendai, held in October 2015 in Manila, Philippines. The authors are also grateful to Prof Yuguo Li and colleagues at the Hong Kong University for funding Dr Yasemin D. Aktas for visiting the Built Environment group for a very fruitful scientific exchange in 2016. The authors also kindly acknowledge the helps of CERC’s Stephen Smith and UCL IEDE’s Dane Virk in the preparation of input files.

References

Aktas, Y. D., D'Ayala, D., Erkal, A., & Stephenson, V. (2015). Environmental performance assessment using monitoring and DVS testing. *Proceedings of the Institution of Civil Engineers - Engineering History and Heritage, 168*(1), 3-16.

Anderson, J. R., Hardy, E. E., Roach, J. T., & Witmer, R. E. (1976). *A Land Use and Land Cover Classification System for Use with Remote Sensor Data.* Washington: Geological Survey Professional Paper 964.

Bohnenstengel, S. I., Evans, S., Clark, P. A., & Belcher, S. E. (2011). Simulations of the London urban heat island. *Quarterly Journal of the Royal Meteorological Society, 137*(659), 1625-1640.

Bretz, S., Akbari, H., Rosenfeld, A., & Taha, H. (1992). *Implementation of solar-reflective surfaces: Materials and utility programs.* Berkeley, California: University of California.

Buchin, O., Hoelscher, M.-T., Meier, F., Nehls, T., & Ziegler, F. (2016). Evaluation of the health-risk reduction potential of countermeasures to urban heat islands. *Energy and Buildings, 114*, 27-37.

Carruthers, D. J., & Weng, W. S. (1992). The effect of changes in surface resistance on temperature and humidity fields and fluxes of sensible and latent heat. *Boundary-Layer Meteorology, 60*(1-2), 185-199.

CERC. (2015). *ADMS-Urban: Urban Air Quality Management System User Guide.* Cambridge: CERC.

D'Ayala, D., & Aktas, Y. D. (2016). Moisture dynamics in the masonry fabric of historic buildings subjected to wind-driven rain and flooding. *Building and Environment, 104*, 208-220.

Grimmond, C. S., & Oke, T. R. (1999). Aerodynamic properties of urban areas derived from analysis of surface form. *Journal of applied meteorology, 38*(9), 1262-1292.

Hajat, S., Kovats, R. S., & Lachowycz, K. (2007). Heat-related and cold-related deaths in England and Wales: who is at risk? *Occup Environ Med, 64*, 93-100.

Hajat, S., Vardoulakis, S., Heaviside, C., & Eggen, B. (2014). Climate change effects on human health: projections of temperature-related mortality for the UK during the 2020s, 2050s and 2080s. *J Epidemiol Community Health, 0*, 1-8.

Hamilton, I., Stocker, J., Evans, S., Davies, M., & Carruthers, D. (2014). The impact of the London Olympic Parkland on the urban heat island. *Journal of Building Performance Simulation, 7*(2), 119-132.

Harrison, A. R. (2006). *National Land Use Database: Land Use and Land Cover Classification.* London: Office of the Deputy Prime Minister.

Heaviside, C., Tsangari, H., Paschalidou, A., Vardoulakis, S., Kassomenos, P., Georgiou, K. E., & Yamasaki, E. N. (2016). Heat-related mortality in Cyprus for current and future climate scenarios. *Science of The Total Environment, 569-570*, 627-633.

Hoshiko, S., English, P., Smith, D., & Trent, R. (2010). A simple method for estimating excess mortality due to heta waves, as applied to the 2006 California heat wave. *International Journal of Public Health, 55*(2), 133-137.

Hunt, J. C., Aktas, Y. D., Mahalov, A., Moustaoui, M., Salamanca, F., & Georgescu, M. (2017). Climate change and growing megacities: hazards and vulnerability. *Proceedings of Institution of Civil Engineers - Engineering Sustainability*, 1-13.

Huynen, M. M., Martens, P., Schram, D., Weijenberg, M. P., & Kunst, A. E. (2001). The Impact of Heat Waves and Cold Spells on Mortality Rates in the Dutch Population. *Environmental Health Perspectives, 109*(5), 463-470.

Jacobson, M. Z., & ten Hoeve, J. E. (2012). Effects of Urban Surfaces and White Roofs on Global and Regional Climate. *Journal of Climate, 25*, 1028-1043.

Kaul, R. N. (1970). *Zones, Afforestation in Arid.* The Hague: Springer.

Mavrogianni, A., Davies, M., Batty, M., Belcher, S. E., Bohnenstengel, S. I., Carruthers, D., . . . Ridley I. (2011). The comfort, energy and health implications of London's urban heat island. *Building Services Engineering Research and Technology, 32*(1), 35-52.

Ojima, T., & Moriyama, M. (1982). Earth Surface Heat Balance Changes Caused by Urbanization. *Energy and Buildings, 1*(3), 99-114.

Oke, T. R. (1987). *Boundary Layer Climates* (2nd ed.). New York: Routledge.

Oke, T. R. (1988). The urban energy balance. *Progress in Physical Geography, 12*(4), 471-508.

O'Neill, M. S., & Ebi, K. L. (2009). Temperature Extremes and Health: Impacts of Climate Variability and Change in the United States. *Journal of Occupational and Environmental Medicine, 51*(1), 13-25.

Owen, B., Edmunds, H. A., Carruthers, D. J., & Singles, R. J. (2000). Prediction of total oxides of nitrogen and nitrogen dioxide concentrations in a large urban area using a new generation urban scale dispersion model with integral chemistry model. *Atmospheric Environment, 34*(3), 397-406.

Salamanca, F., Georgescu, M., Mahalov, A., Moustaoui, M., & Wang, M. (2014). Anthropogenic heating of the urban environment due to air conditioning. *Journal of Geophysical Research: Atmospheres, 119*(10), 5949-5965.

Skamarock, W. C., Klemp, J. B., & Dudhia, J. (2008). *A description of the advanced research WRF version 3: NCAR Technical Note NCAR/TN-475+STR.* Boulder, Colorado, USA: Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research.

Stidworthy, A., Carruthers, D., Stocker, J., Balis, D., Katragkou, E., & Kukkonen, J. (2013). MyAir Toolkit for Model Evaluation. *15th International Conference on Harmonisation.* Madrid, Spain.

Stull, R. B. (1988). *An Introduction to Boundary Layer Meteorology.* Dordrecht: Kluwer Academic Publishers.

Taha, H., Akbari, H., A, R., & Huang, J. (1988). Residential cooling loads and the urban heat island - the effects of albedo. *Building and Environment, 23*(4), 271-283.

Touchaei, A. G., Akbari, H., & Tessum, C. W. (2016). Effect of increasing urban albedo on meteorology and air quality of Montreal (Canada) – Episodic simulation of heat wave in 2005. *Atmospheric Environment, 132*, 188-206.

Virk, G., Jansz, A., Mavrogianni, A., Mylona, A., Stocker, J., & Davies, M. (2014). The effectiveness of retrofitted green and cool roofs at reducing overheating in a naturally ventilated office in London: Direct and indirect effects in current and future climates. *Indoor and Built Environment, 23*(3), 504-520.

Virk, G., Jansz, A., Mavrogianni, A., Mylona, A., Stocker, J., & Davies, M. (2015). Microclimatic effects of green and cool roofs in London and their impacts on energy use for a typical office building. *Energy and Buildings, 88*, 214-228.