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# THE IMPACT OF CITY SCALE MORPHOLOGICAL AND ANTHROPOGENIC HEAT PARAMETERS ON DAILY TEMPERATURE CYCLES

Yi Wang[a],*, Yuguo Li[a]

[a]*Department of Mechanical Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong SAR, China*

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## Abstract

Urban heat island (UHI) is generally considered to be one of the major problems to human beings due to accelerated urban growth and anthropogenic heat release. To further investigate the cause of UHI, an improved Zero-dimensional City Air Temperature (zCAT) model was proposed for analyzing urbanization effect on urban thermal environment and applied to the city of Hong Kong. Comparison of model result with measured meteorology data revealed that the improved model was able to predict daily varying urban air temperature with good accuracy, with insignificant effect on the model performance based on different weather condition. We conclude that building height and plan area ratio play an important role on daily cycle of urban air temperature.

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*Keywords:* zCAT model, Urban heat island, urban thermal environment

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## 1. Introduction

Urban heat island (UHI) is generally considered to be one of the major problems to human beings due to accelerated urban growth and anthropogenic heat release [1]. In the past decades, many urban canopy models (UCM) have been developed for improving our theoretical understanding of the phenomenon [2]. However, the current models are inevitably inadequate to link the response of the urban air temperature to the urban morphology in a quantitative way.

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* Corresponding author. Tel.:+852-97196345; fax:+852-28588415.
*E-mail address:* wangyi27@connect.hku.hk

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Silva [3] developed a zero-dimensional mesoscale thermal model to allow the users to rapidly predict a characteristic urban temperature. However, the model result does not represent either the surface or air temperature in practice.

In this article we present an improved Zero-dimensional City Air Temperature (zCAT) model that couples the air energy balance and surface energy budget. The outcomes of the new model are to provide quantitative understanding of urban thermal environment variation. The comparison result of model prediction and measured data highlights the importance of coupling the two energy balance equations for more accurate prediction of urban air temperature. The improved model can provide effective strategies for mitigating UHI phenomenon.

## 2. Model description

### 2.1. Governing equations

In this model, we choose the most widely used single-layer canopy model. We consider the urban air being well mixed and the air temperature as uniform. There are two energy balance equations in the model, i.e. the city air energy balance (1) and urban surfaces energy balance (2), respectively.

$$qC_pq(T_r - T_u) + h_c(T_s - T_u)A_b + A_pq_a = 0 \quad (1)$$

where the first term is net advection from rural to urban areas; the second term is convective heat transfer between urban surfaces and atmosphere; and the last term is anthropogenic heat flux into the atmosphere. Note here that $A_b$ is built area (sum of road, $A_{ps}$; roof, $A_{pr}$; natural surfaces, $A_{pn}$; and wall areas, $A_{bw}$); $A_p$ is plan area (obtained from map or aerial photo) [4]; $T_r$ is rural air temperature; $T_u$ is urban air temperature and $T_s$ is urban surface temperature. Note here that the rural air and surface temperature can be approximated written by using Fourier series

$$T_r = \bar{T}_r + \sum_{j=1}^{n}(T_{r1j}\cos jmt + T_{r2j}\sin jmt).$$

$$q_{cd(0,t)}A_b = (1-\alpha)q_sA_p\downarrow - q_e A_{pn}\uparrow - q_{cr}A_b\uparrow - q_r A_b\uparrow \quad (2)$$

where $q_{cd(0,t)}$ is conductive heat flux at the urban surface level; and $q_s$, $q_e$, $q_{cr}$ and $q_r$ are incoming time-dependent solar radiation, latent heat flux (evaporation or evapotranspiration), convective heat flux and outgoing longwave radiation respectively. Downward and upward errors denote downwelling and upwelling process.

Note here that we assume the unknown diurnal variation of urban surface temperature, $T_s$[5], can be approximated written by using Fourier series.

$$T_s(0,t) = \overline{T_s} + \sum_{j=1}^{n}(T_{s1j}\cos jmt + T_{s2j}\sin jmt) \quad (3)$$

Note here that we assume the surface is homogeneous and the heat flux is merely transferred in the vertical direction. Hence the heat conduction equation can be written as

$$\frac{6T_s}{6t} = \frac{ß_p}{¢}\frac{6^2T_s}{6z^2} \quad (4)$$

Here $ß_p$ is conductive heat transfer coefficient. C is the volumetric heat capacity of urban surfaces. Then the solution of Eq. (4) may be written as

$$T_s(z,t) = \overline{T_s} + \sum_{j=1}^{n} e^{-\alpha_j z}[T_{s1j}\cos(jmt - \alpha_j z) + T_{s2j}\sin(jmt - \alpha_j z)] \quad (5)$$

Here $\alpha_j = \mathbf{J}\frac{jm}{2a_p}$, where $a_p = \frac{ß_p}{¢}$ is thermal diffusivity. Note here that $d_j = \mathbf{J}\frac{2a_p}{jm}$ is the penetration depth of the force. Here $m = \frac{2n}{24\times3600} = 7.27\times10^{-5}$ 1/s, provided time given in seconds. Then

$$q_{cd(0,t)} = -ß_p \left.\frac{dT_s(z,t)}{dz}\right|_{z=0} = ß_p \sum_{j=1}^{n} \alpha_j[(T_{s1j} + T_{s2j}) \cos jmt + (T_{s2j} - T_{s1j}) \sin jmt] \quad (6)$$

### 2.2. Time-dependent Solar radiation

Note here that the hourly incident solar radiation measured by Hong Kong Observatory can be directly used and

that we assume the diurnal variation of solar radiation flux, $q_{so1}$, can be approximated by using Fourier series.

$$q_s = \bar{q_s} + \sum_{j=1}^{n} (q_{s1j} \cos jmt + q_{s2j} \sin jmt) \quad (7)$$

### 2.3. Longwave radiation

The outgoing longwave radiation from each urban surfaces arises from the Stefan-Boltzmann law.

$$q_r = F_{sky} so({T_s}^4 - {T_{sky}}^4) \approx h_{rad}(T_s - T_{sky}) \quad (8)$$

where $F_{sky}$ is the sky view factor of the urban areas, s is emissivity, o is the Stefan-Boltzmann constant, $o = 5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$, $T_{sky}$ is the effective temperature of the sky, which is related to the air relative humidity and dew point, $h_{rad} = 4so\bar{T}^3$, $\bar{T}$ is the mean of $T_s$ and $T_{sky}$.

$T_{sky}$ can be evaluated as [3]

$$T_{sky} = T_r(0.004T_{dew} + 0.8)^{0.25} \quad (9)$$

where $T_{dew}$ is the dew point temperature. Note here that $T_{sky}$ can be written as

$$T_{sky} = \bar{T}_{sky} + \sum_{j=1}^{n} (T_{sky1j} \cos jmt + T_{sky2j} \sin jmt) \quad (10)$$

### 2.4. Convective and latent heat fluxes

One factor of the heat loss/gain is due to convective heat transfer. Due to the assumption of uniform urban air temperature, the convective heat flux can be expressed as

$$q_{cr} = h_c(T_s - T_u) \quad (11)$$

where the convective heat transfer coefficient is related to the wind velocity in the urban environment [6].

Another factor of the heat loss is latent heat flux, which is more complex inside the urban canopy layer. The most common used method is Bowen's ratio method using the ratio of sensible heat flux to the latent heat flux [7]. The second method for estimating latent heat flux uses the following formula [3],

$$q_e = E_t q_{K_20} L_r \quad (12)$$

where $E_t$ is the measured hourly evaporation or evapotranspiration in meters and $L_r$ is latent heat of vaporization. Note here that $q_e$ can also be approximated by using Fourier series.

$$q_e = \overline{q_e} + \sum_{j=1}^{n} (q_{e1j} \cos jmt + q_{e2j} \sin jmt) \quad (13)$$

### 2.5. Anthropogenic heat flux

Due to limited measurement data available in Hong Kong, we incorporate anthropogenic data Ichinose [8] provided for Tokyo in our model for validation. Also note here that $q_a$ is also approximated by using Fourier series.

$$q_a = \overline{q_a} + \sum_{j=1}^{n} (q_{a1j} \cos jmt + q_{a2j} \sin jmt) \quad (14)$$

## 3. Simulated results and discussion

In this section, we choose Kowloon Peninsula as the target area with a plan area of 47 km$^2$. We choose two weather stations, Hong Kong Observatory Headquarters (HKO, 32m, 22°18’07”N, 114°10’27”E, located in Tim Sha Tsui, the core urban area of Kowloon) and Ta Kwu Ling (TKL, 15m, 22°31’43”N, 114°09’24”E, located in the northeast of the New Territories with lush vegetation but low dense population) as urban and rural area respectively. We choose the calm and cloudless days from the hourly air temperature data from 1994 to 2013. The meteorological data is provided as input data in the model.

The analytical solution with the time step of 1min provides us the possibility for further analysis. Input parameters for urban morphology and surface material thermal properties are tested by Yang [9] in the same target area. Fig. 1 shows results of comparison of the model predictions of urban air temperature and measured 2-m air temperature in TKL and HKO. The model can reasonably recapture the basic characteristics of the urban air temperature. The maximum and minimum temperature are roughly in agreement with the measured temperature though slightly offset in time. The diurnal range of model result and observational data are 5.18℃ and 4.72℃ respectively.

The urban morphology, anthropogenic heat and other factors could influence the average, amplitude and phase term of the urban air temperature. Fig.2 provides us trend of the mean value, amplitude and phase shift of the urban air temperature based on the variation of building height and plan area ratio respectively.

The model shows that the average temperature, amplitude and phase shift of the urban air temperature sharply decrease initially and then it tends to stabilize if continuously increasing the building height. When the building height increases to satisfy the high compact and high dense city criteria, the solar radiation may not go through the urban street due to the shadow areas and block effect in the area which leads to the declination of mean temperature and phase term and there exists more urban surfaces for thermal storage due to the larger building wall areas which leads to the declination of amplitude. When the building height is lower, the longwave radiation to the sky is much larger and the absorbed solar radiation is also larger, so thus causes the large amplitude value.

In Fig. 2(b), with the increase of natural surfaces, with respect to the decrease of the urban building area, the mean temperature value slightly increases; the phase shift is advanced while the amplitude increases. When the building area ratio declines, which means that the thermal storage is lower, then the phase shift is advanced and combined with the large diurnal temperature range.

There exists other factors which may affect the urban air temperature which contains the impervious urban materials properties, urban canyon geometry parameters, like urban albedo, sky view factor, etc. In this section, we consider the relative importance of individual factors in a nondimensional way and then establish the relative comparison of these factors. The dimensionless relationship is provided by Gui et al. [10], which make the parameters with different units and ranges comparable in the equation.

$$\frac{6D}{6(\text{factor})^*} = \frac{\frac{\frac{6D}{6(\text{factor})}}{D_{\text{ref}}}}{\Delta(\text{factor})} \quad (15)$$

where $\frac{6D}{6(\text{factor})}$ means change in the mean value (or amplitude or phase time) of the urban air temperature with respect to a specific influencing factor value. Thus is taken with respect to the reference value of the mean value (or amplitude or phase time) with the original influencing factor value and the range of the factor value. Fig. 3 summarizes the relative effect of different strategies on the mean value (or amplitude or phase time) of the urban air temperature, with double decreasing the property parameters, which are shown in Table 1. When changing each parameters, with the highest increase in the mean temperature by decreasing the building height, $h$, followed by sky view factor and albedo. Declination of ACH could lower down the amplitude value with the other two indicators similar as the standard case which may be better for our urban thermal environment, but we need to suffer with less ventilation rate which may cause poor air quality in the urban canopy layer. This relative effects of the parameters could provide us practical mitigation strategies on the thermal environment under different urban morphology.

Table 1. Influencing factors on urban air temperature of the study area

| Parameters | Standard case | Parameter variation |
|---|---|---|
| albedo (-) | 0.5 | 0.25 |
| Sky view factor (SVF) (-) | 0.3 | 0.15 |
| ACH (-) | 3.5 | 1.75 |
| $h$ (m) | 80 | 40 |
| $v$ (m/s) | 5.0 | 2.5 |
| $f_r$ (-) | 0.55 | 0.275 |
| $f_n$ (-) | 0.20 | 0.10 |
| C (MJ $K^{-1}$ $m^{-3}$) | 2.7 | 1.35 |

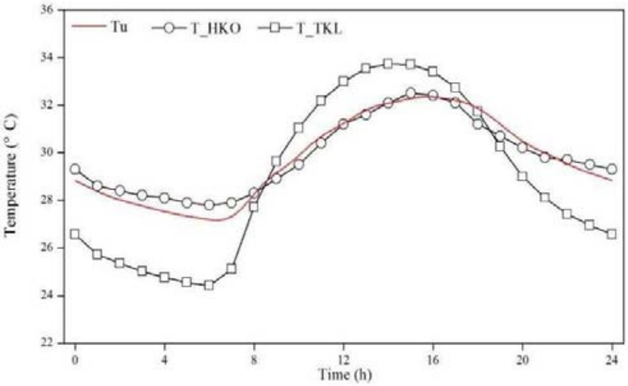

Fig. 1. Performance of ZCAT model with measured 2-m air temperature for HK in July

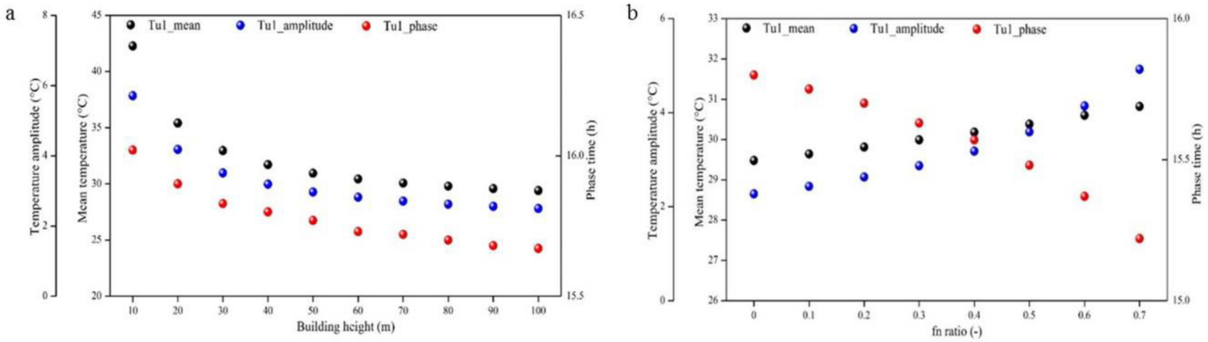

Fig. 2. Urban air temperature in terms of mean temperature, amplitude and phase shift for different (a) building height and (b) plan area ratio

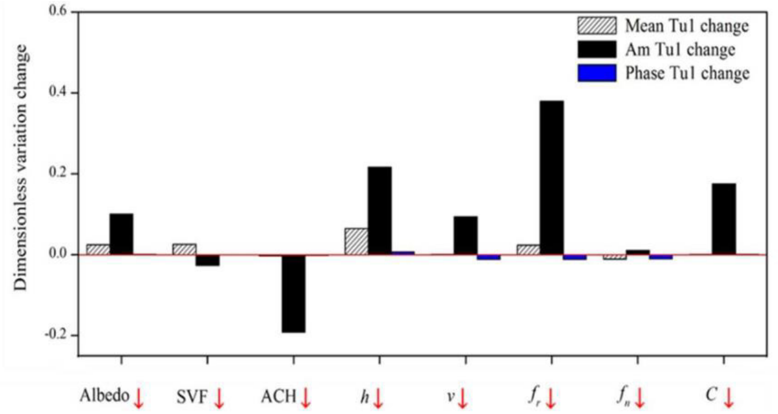

Fig. 3. Relative effect of influencing factors on urban air temperature

## 4. Conclusion

An improved Zero-dimensional City Air Temperature (zCAT) model is provided aiming at further analysis urban heat island phenomenon in theory. The improved model could better recapture the basic characteristics of the urban air temperature and show good accuracy. The urban morphology, anthropogenic heat and other factors could influence the three components (mean temperature, amplitude and phase shift) of the urban air temperature. However, we made a lot assumptions in the model, which may limit the accuracy of the results. Thus the future work we need to classify the urban surfaces into different categories to cater the more realistic situation.

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