Modelling the impact of building energy consumption on urban thermal environment: The bias of the inventory approach

Liutao Chen[1], Jiachuan Yang[1,*]

[1] Department of Civil & Environmental Engineering, Hong Kong University of Science and Technology, HKSAR, China (email: chenlt@ust.hk)

香港科技大學 THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Background

Anthropogenic heat (AH) generated by human activities in urban is an important cause of the urban heat island (UHI). In 2021, building sector accounted for 34% of total final energy use, and heat release from buildings is the largest contributor to heat emissions globally.

Appropriate estimates of AH are critical to understand the impact of human activities on urban thermal environment. The **Inventory (IVT) approach** and **Building Energy Modelling (BEM)** are the most used methods to estimate building waste heat.

However, the assumptions of **IVT approach** can lead to over or under-estimation of air and surface temperatures in the urban canyon. The **BEM approach**, considering the dynamic interaction between the outdoor microclimate and indoor environment, provides a reliable way to quantify the building waste heat impact on urban climate.

(a) IVT approach:

$$R_n + BEC = Q_H + Q_{LE} + Q_G + Q_s$$

National Energy Statistics → Gridded energy data → Put into climate models as source term

Map by gridded surrogates: Population density data, land use data, building dataset, etc

Assumption:
Building energy consumption (**BEC**) = waste heat emission (**BWH**), No time lag, No latent heat component.

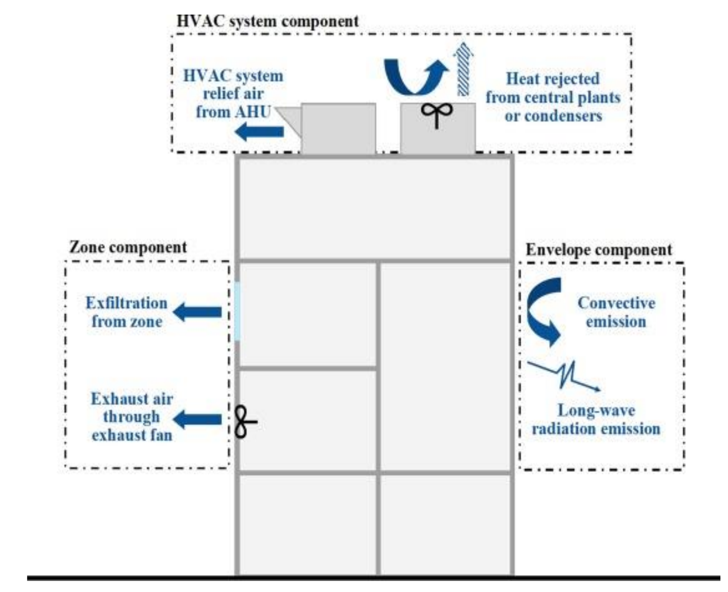
(b) BEM: Physics-based simulation of energy use.

$$BEC = Q_{Equip} + Q_{Occup} + Q_{HVAC}$$

Direct contribute to indoor thermal balance ($Q_{Equip} + Q_{Occup}$)

Heating/Cooling systems maintain room comfortable (Q_{HVAC})

Building heat emissions from:
(1) Envelope, (2) Zones, and (3) HVAC system.



Research Questions

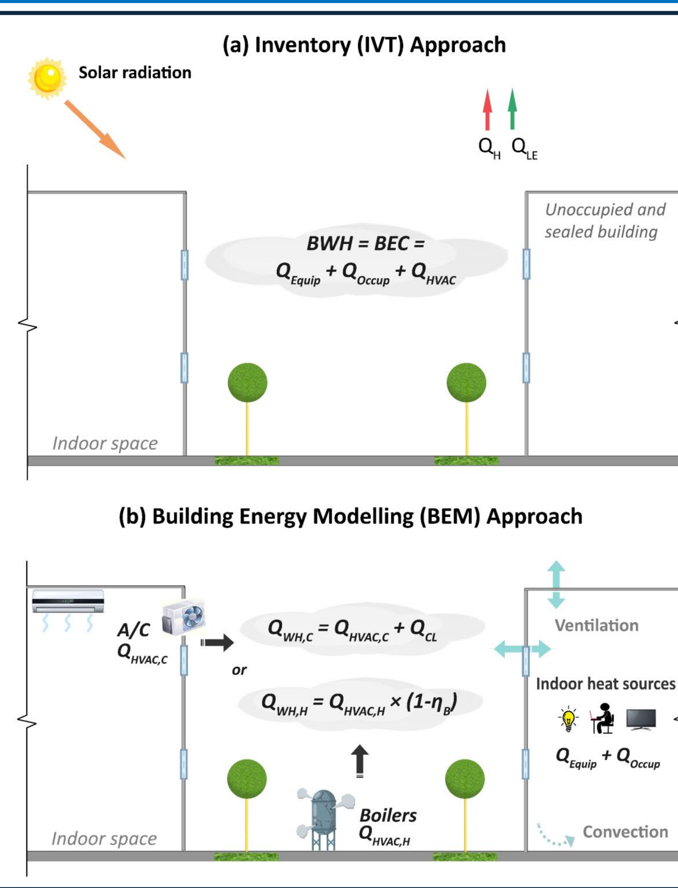
Considering the temperature bias caused by IVT approach has not been systematically investigated, we aim to address following questions:

1. What are the impacts of building energy consumption (BEC) on urban thermal environment?
2. If we assign same BEC to urban neighbourhoods, how large the temperature biases caused by IVT approach compared to BEM?

Methods

Single-Layer urban canopy model coupled with Building energy model (BEM-SLUCM)

We conduct simulations in Beijing for three building types (residential, office, and hotel) and LCZs 1-9 in January & July to reveal the **temperature biases (ΔT_{can}) by the IVT** approach, using the results from the BEM approach as the ground truth.



Different response of T_{can} by two approaches:

IVT:

$$\frac{dT_{can}}{dt} = \frac{1}{\rho_a c_p Z_B}\left(Q_{H,G} + 2h \times Q_{H,W} + BEC - Q_{H,can}\right)$$

$$\frac{dq_{can}}{dt} = \frac{1}{\rho_a \lambda_v Z_B}\left(Q_{LE,G} - Q_{LE,can}\right)$$

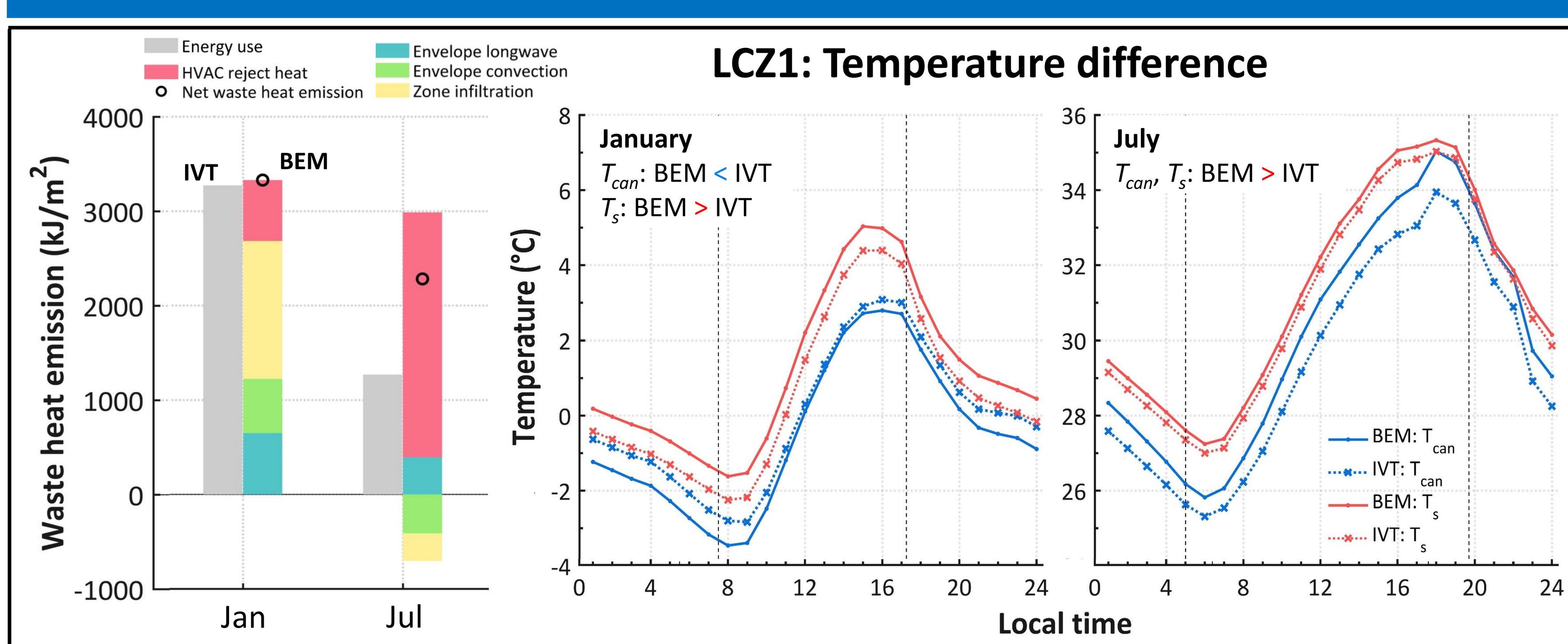
BEM:

$$\frac{dT_{can}}{dt} = \frac{1}{\rho_a c_p Z_B}\left(Q_{H,G} + 2h \times Q_{H,W} + Q_{H,WH} - 2h \times Q_{H,vent} - Q_{H,can}\right)$$

$$\frac{dq_{can}}{dt} = \frac{1}{\rho_a \lambda_v Z_B}\left(Q_{LE,G} + Q_{LE,WH} - 2h \times Q_{LE,vent} - Q_{LE,can}\right)$$

Results

LCZ1: Temperature difference



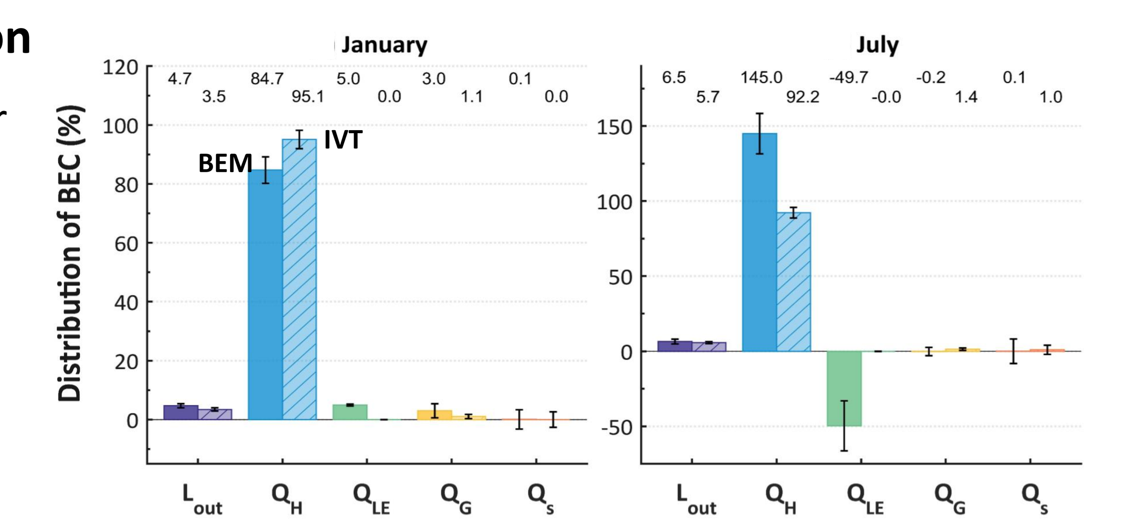
Difference of BEC dissipation

Jan Boilers: 75% heat for indoor warming, 25% to outdoor.

Q_H: 10.4% ↑, Q_{LE}: 5.0% ↓

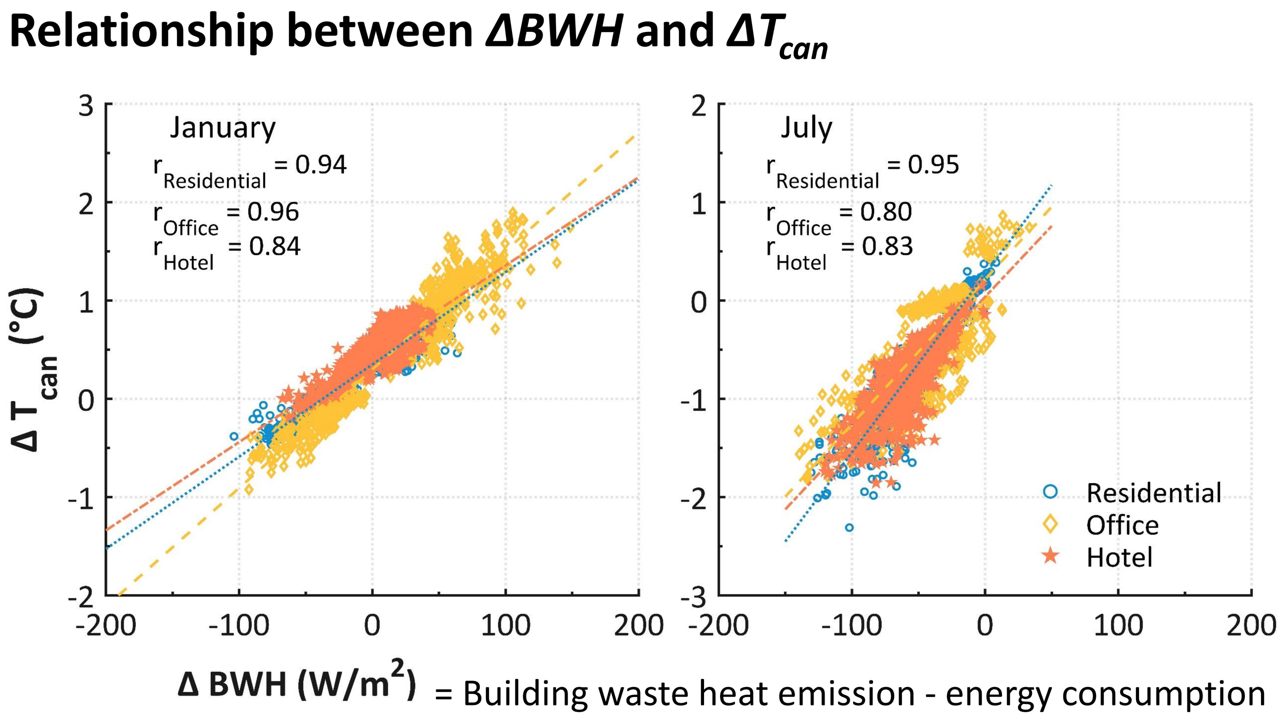
Jul A/C helps to dehumidify: Remove indoor Latent heat -> Sensible waste heat

Q_H: 52.8% ↓, Q_{LE}: 49.7% ↑



Window-type A/C might enhance urban heat and dry island

Relationship between ΔBWH and ΔT_{can}



ΔBWH (W/m²) = Building waste heat emission - energy consumption

+ 1 W/m² in ΔBWH, + 0.015 °C in ΔT_{can}

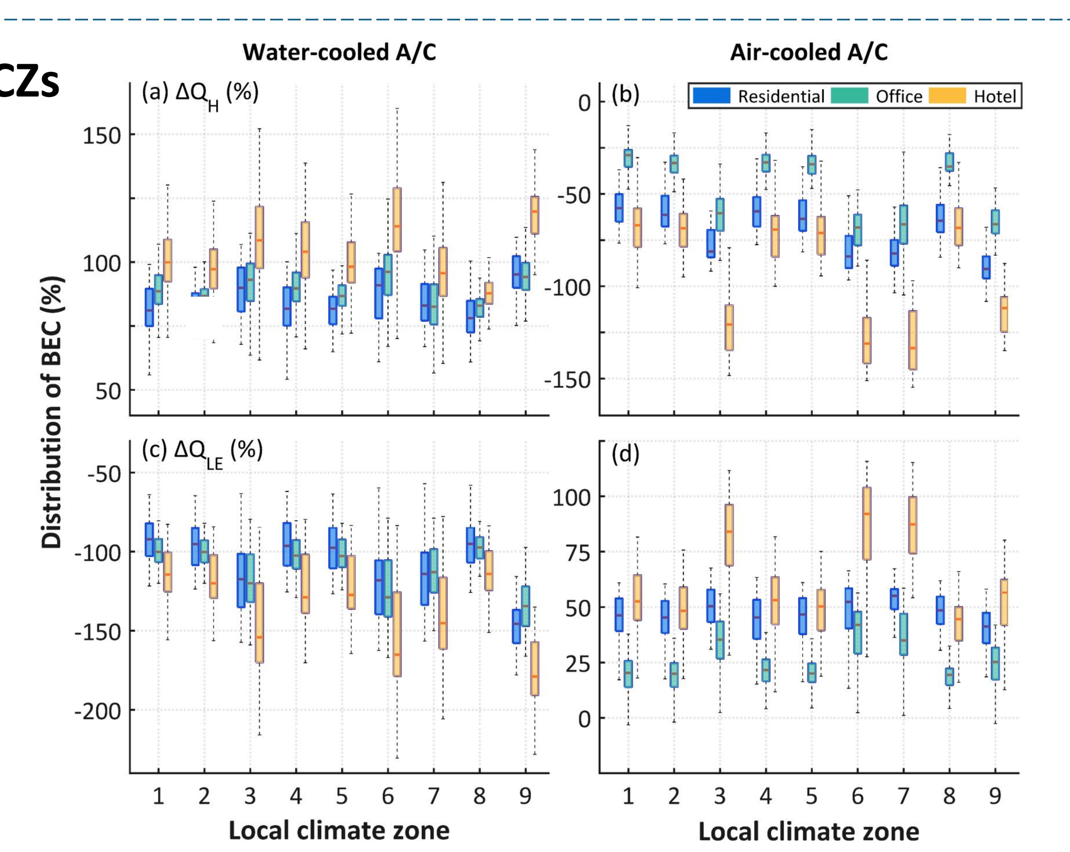
Larger discrepancy between waste heat & energy use tends to yield larger bias on T_{can}

Influence of A/C type across LCZs

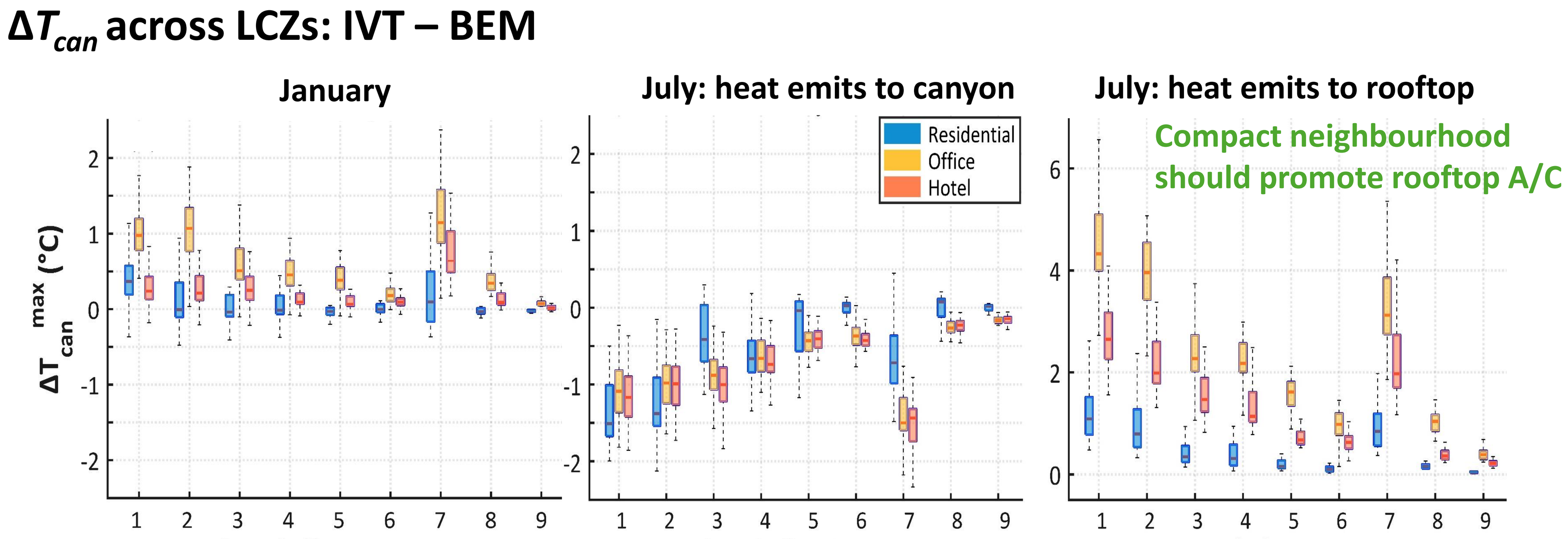
Different A/C types have great influence on the distribution of BEC into Q_H and Q_{LE}

Water-cooled A/C scenario:
IVT overestimate Q_H up to 118%↑,
Underestimate Q_{LE} up to 178%↓.

Hotel buildings: A/C operates all day continuously.



ΔT_{can} across LCZs: IVT – BEM



- Higher ΔT_{can}^{max} in office: BEC is larger during the working hours. IVT approach neglect building heat storage effect, and it directly adds BEC in canyon, causing rapid T_{can} increase.
- When the peak BWH hours coincide with the hottest time of the day, IVT can cause large bias in LCZ 1, 2, and 7, which indicates **canyon aspect ratio** and **building surface fraction** are the key factors that influence AH-derived warming.

Conclusion

- The IVT approach demonstrates limitations in evaluating the impacts of BEC on T_{can}, especially when accounting for the efficiencies of heating and A/C systems:
  - **Temperature Accuracy**: IVT ↑T_{can}^{max} by over 1°C in Jan. In July, it ↓T_{can}^{mean} by 1.2°C when A/C heat emissions at canopy and ↑ by 2.1°C at the rooftop.
  - **Impact of A/C Type**: The A/C type significantly influences the redistribution of BEC into Q_H & Q_{LE} heat, with IVT often ↑Q_H & ↓Q_{LE}, indicating a possible overestimation of urban heat/dry island (except window type A/C scenario).
- Larger differences between building waste heat and energy use lead to greater biases in T_{can} predictions, highlighting the **critical need for accurate waste heat assessments**.
- Compact and high-rise neighborhoods would benefit from adopting rooftop and water-cooled A/C systems to mitigate adverse heating impacts.

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