Spatiotemporal impact of vehicle heat on urban thermal environment: a case study in Hong Kong

Introduction

Anthropogenic heat (AH) is widely known as one major cause of the urban heat island (UHI) effect. But while studies have focused on the impact of *aggregated* anthropogenic heat on the urban thermal environment, the impact of individual components of AH has been less explored (Bohnenstengel et al., 2014). Vehicle heat (VH) is generally recognized as the second-largest contribution to the AH (Quah & Roth., 2012; Smith et al., 2009), and there have been only a few studies on the separate impact of VH. Zhu et al. (2017) estimated hourly gridded VH profiles in Hong Kong and found a robust correlation between VH and UHI intensity. Singh et al. (2020) integrated hourly spatial VH data into regional climate simulations and estimated the impact of VH over Singapore during April. However, the study used a mean VH profile for the entire simulation period, meaning that the differences between weekday and weekend are neglected. Until now, the spatial and temporal variations of the VH impact on the thermal environment over diverse urban landscapes still remain unclear.

In the present study, we chose Hong Kong as an example to investigate the spatiotemporal impact of vehicle heat on the urban thermal environment. The study integrated fine-resolution urban canyon parameters (Zheng et al., 2018), building heat data based on the local climate zone map, and gridded vehicle heat data (Zhu et al., 2017) into WRF-SLCUM (Weather Research and Forecasting – single-layer urban canopy model) numerical simulations.

Methodology

Numerical experiments

Three simulation scenarios were considered in summer: 1) a reference case (NoAH) without anthropogenic heat, 2) a case (BH) with the LCZ based building heat emission, and 3) a vehicle heat case (VH) with building heat and vehicle heat. Because of the sub-tropical climate of Hong Kong, building waste heat is not important in winter (Wang et al., 2018). We conducted only two simulations in winter: a reference case (NoAH) without anthropogenic heat and a vehicle heat case (VH) with vehicle heat. The simulation periods were from 1st July 00:00 (UTC) to 15th July 00:00 (UTC) and from 1st January 00:00 (UTC) to 15th January 00:00 (UTC), 2015.

Vehicle heat data

Hourly gridded vehicle heat data in Hong Kong for weekdays, Saturday, and Sunday at 800 m × 800 m resolution were adopted from Zhu et al. (2017). We resampled the original vehicle heat data (800 m × 800 m resolution) to match the innermost WRF domain (500 m × 500 m resolution) by linear interpolation. Fig. 1a shows the spatial distribution of weekly mean VH (time-averaged VH over one weekly cycle) over Hong Kong. The grids with high VH values were mainly concentrated at four core districts with dense road networks, as shown in Fig. 1b. Fig. 1c shows the temporal profile of VH in all grids (red line, right axis).

Results

Temporal variation of VH impact

We look into the temporal variation of the impact of vehicle heat during weekdays, Saturday and Sunday through the difference in the urban sensible heat flux (ΔSH^{urb}) and urban canyon air temperature (ΔT_2^{urb}). Figure 2 shows that ΔSH^{urb} is larger in the daytime, especially around or after the rush hours. The standard deviation of ΔSH^{urb} during daytime is found to be larger than that during nighttime. And it is clear that the summer standard deviations are larger than the winter ones. The changes in regional atmospheric forcing disturb the urban climate and contribute to the large variation of VH impact in summer. After adding VH profiles, WRF-simulated 2-week mean T_2^{urb} increases by 0.32 °C in summer and by 0.35 °C in winter over the VH emission area. The VH impact becomes uniform in summer with a smaller standard deviation.

Spatial variation of VH impact

Fig. 3 shows the spatial distribution of ΔT_2^{urb} over Hong Kong in summer and winter. Results at different time periods throughout the diurnal cycle are presented. VH emissions increase T_2^{urb} over most land areas (positive ΔT_2^{urb}) during all the time periods in summer. From 8 am to 10 am (Fig. 3a), 92% of the Hong Kong land area experiences a higher urban canyon air temperature, with a spatial mean of 0.12 °C. The VH impact becomes weaker on summer nights due to the weak VH emission. The VH impact on urban canyon air temperature is more noticeable and concentrated around the road network in winter (Fig. 3e – 3h). During the winter morning and afternoon rush hours (Fig. 3e and Fig. 3f), around 67% of the land area experiences increased T_2^{urb} by VH. The largest spatial mean ΔT_2^{urb} of 0.16 °C occurs during 11 pm – 1 am (Fig. 3h).

Relationship between VH impact and urban morphology

To diagnose the VH impact on the thermal environment in different urban neighbourhoods, we examine the relationship between the VH impact and urban morphology. A general increasing trend is found between ΔT_2^{urb} and the urban area fraction (FRC), and between ΔT_2^{urb} and mean building height (MH) for the entire land area in

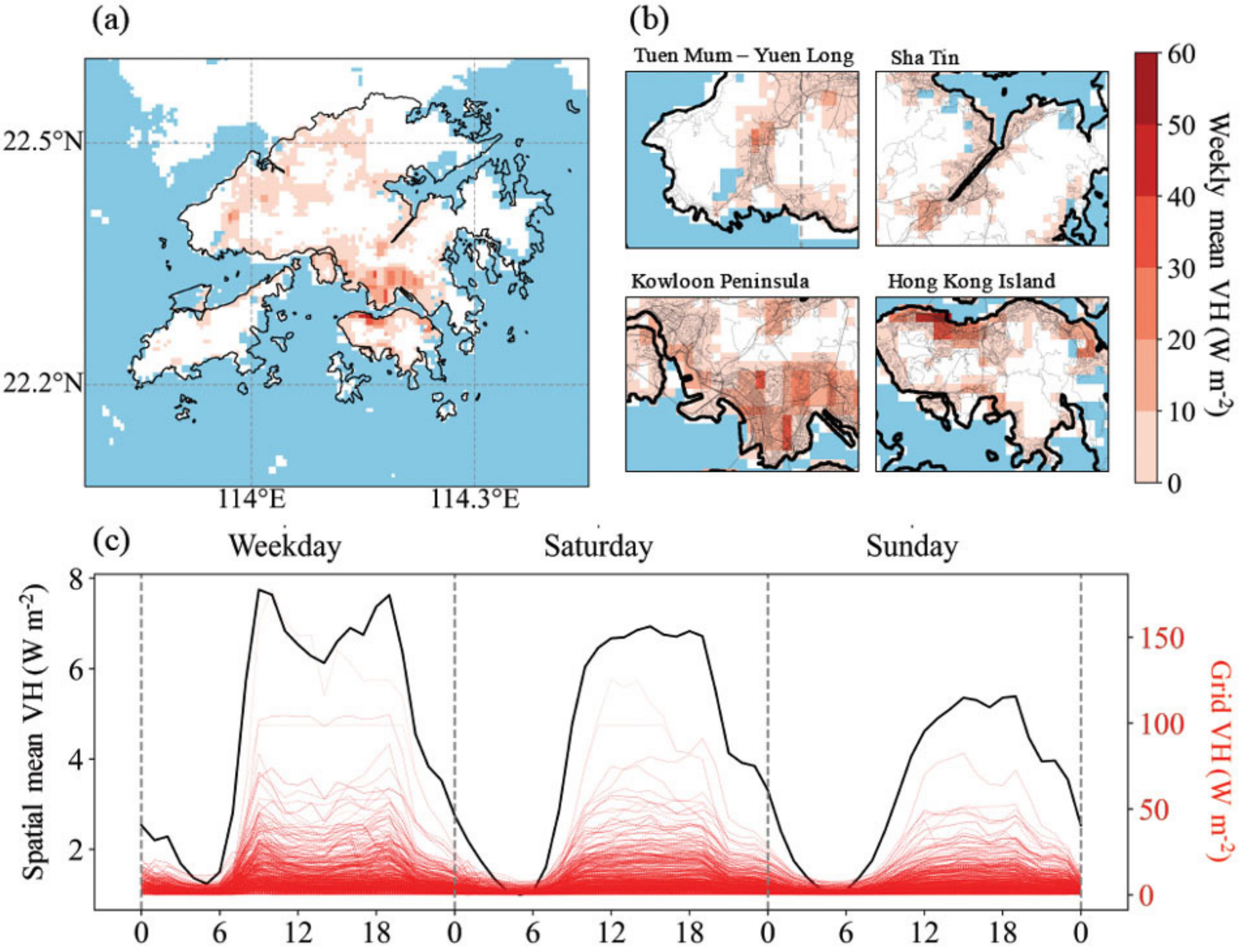

Figure 1. Spatial distribution of the weekly mean VH over (a) Hong Kong and (b) four core districts; (c) Temporal profile of VH in individual grids (red, right axis) and the spatial mean VH profile (black, left axis).

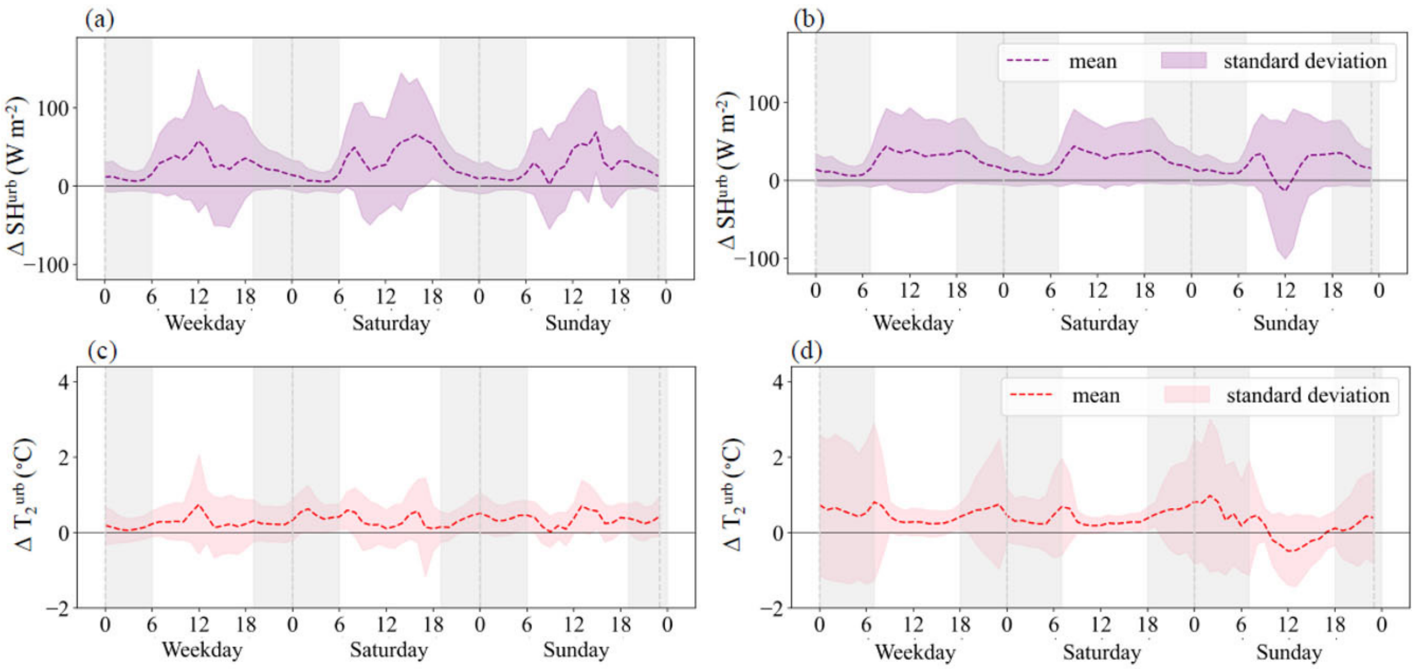

Figure 2. Differences of (a) SH^{urb} in summer, (b) SH^{urb} in winter, (c) T_2^{urb} in summer, and (d) T_2^{urb} in winter. Dashed lines represent the mean differences and the shaded areas represent one standard deviation. The grey (white) color represents the nighttime (daytime) period.

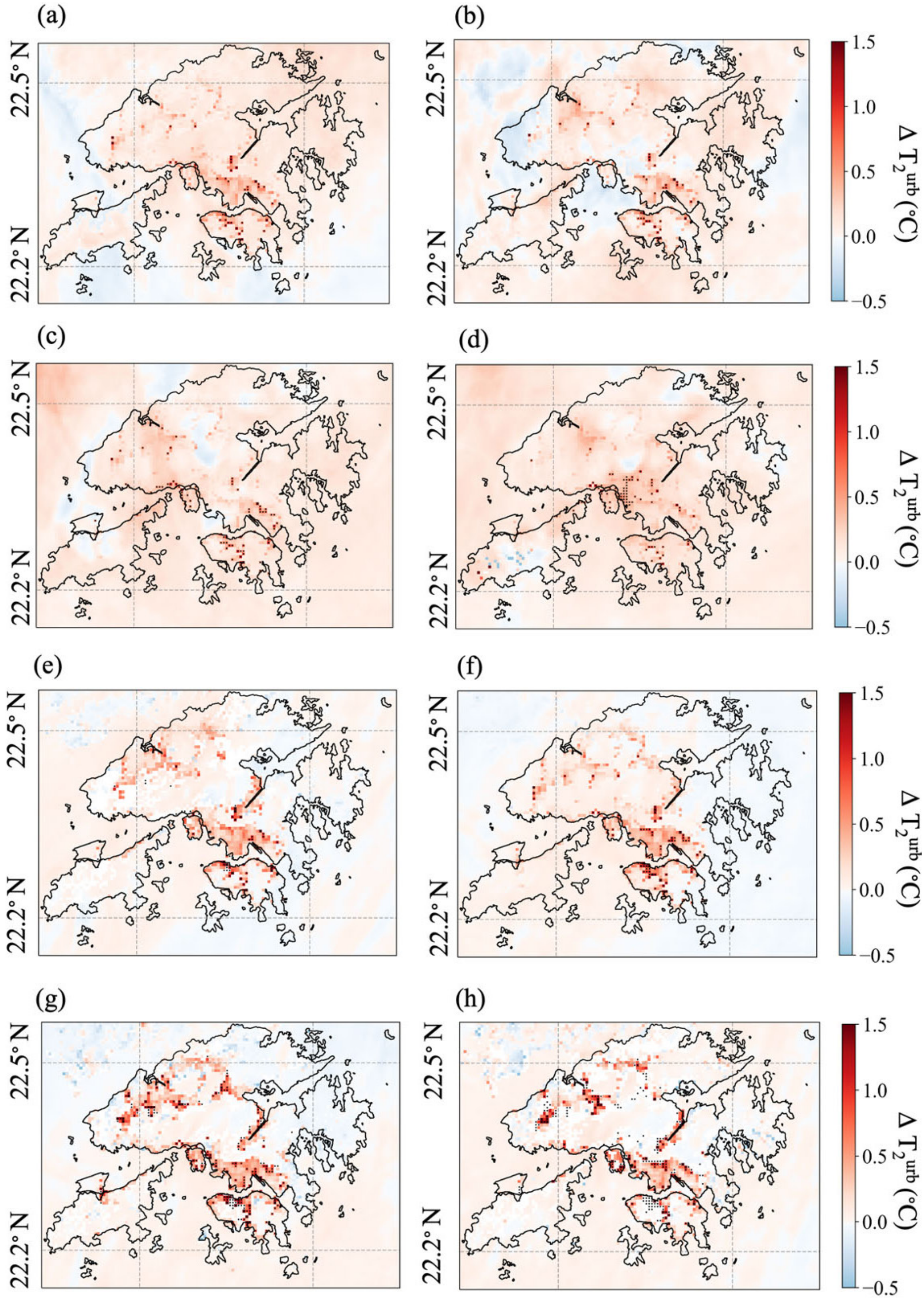

Figure 3. Spatial distribution of ΔT_2^{urb} by VH over Hong Kong in summer: (a) 8 am – 10am, (b) 5 pm – 7 pm, (c) 8 pm – 10 pm, (d) 11 pm – 1 am. Dotted areas stand for regions with impacts statistically significant at the 0.1 level. (e – h) are the same as (a – d) but for winter.

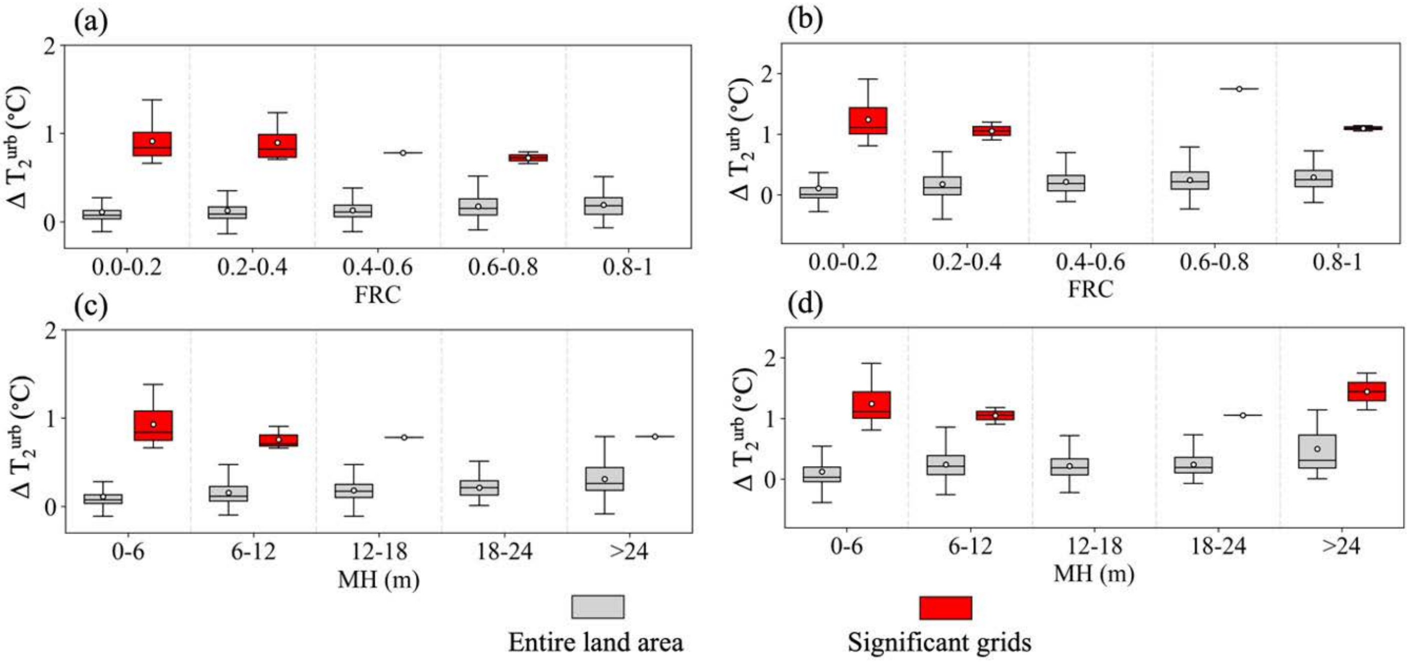

Figure 4 Distribution of ΔT_2^{urb} over different ranges of (a-b) urban area fraction (FRC) and (c-d) mean building height (MH), during 8 am – 10 am (morning rush hours) in summer (left) and winter (right). Significant grids denote the areas with vehicle heat impact statistically significant at the 90% confidence level.

summer and winter (Fig. 4). The significant ΔT_2^{urb}means the area has a high possibility to experience a warmer environment throughout the whole study period due to VH. The large value of the ΔT_2^{urb} can be found in the lowest and the highest MH groups in winter. The major reason is that the VH is released along the roads, and many highways and city circulation roads with large traffic flow are located in low urbanized areas in Hong Kong, such as along the seashore or near mountains. On top of this, part of the highly urbanized neighbourhoods and/or high-rise building areas are downtown regions with dense traffic, where the VH can be trapped among the buildings.

Comparison of VH and building heat impacts

Over the entire land area, the total ΔT_2^{urb} under the combined effect of VH and BH increases with FRC and MH in the morning and at night. This indicates a hotter thermal environment in more urbanized regions. In the morning, Fig. 5a shows that the increase of ΔT_2^{urb} is mainly caused by BH. VH contributes 45% (31%) of the total ΔT_2^{urb} for the areas with FRC of 0-0.2 (0.8-1). Similar trends are observed at night over the entire land area (Fig. 5b). Vehicle heat dominates over building heat in regulating the urban thermal environment only over a small portion of Hong Kong land area. Nevertheless, the warming effect of VH is so strong in these areas that total ΔT_2^{urb} can be three times larger than the mean ΔT_2^{urb} by anthropogenic heat over the whole Hong Kong.

Conclusions and future work

This study incorporates VH and urban landscape data into the Weather Research and Forecasting (WRF) model to estimate the VH impacts at a fine spatial resolution over Hong Kong. Results show a strong temporal variation of the VH impact at daily, weekly, and seasonal scales: 1) the increase in temperature of urban canyon air is stronger and more consistent at night than in daytime, 2) increases in sensible heat fluxes are more pronounced during weekdays than weekends, 3) the temperature change of 0.35 °C in winter is larger than that of 0.32 °C in summer. Increased air temperature over the land area by VH correlates positively with urban area fraction and building height. The relative VH impact compared to building heat demonstrates the dominative role of vehicle heat in warming low urbanized areas with highways and circulation roads.

For mitigation of and adaptation to global warming, governments have encouraged the adoption of highly energy-efficient electric vehicles (EV) as a measure to reduce greenhouse gas emissions in the past decade (International Energy Agency, 2019). By fully or partly replacing internal combustion engines with electric motors, transformation to electric vehicles can markedly cut waste heat from traffic in cities (Ribeiro et al., 2021). Promoting electric vehicles thus has potentials to reduce urban heat islands and benefit the urban thermal environment. The spatiotemporal distributions of the VH impact provide insights into the potential benefits of green transportation technology and policy in mitigating urban heat islands.

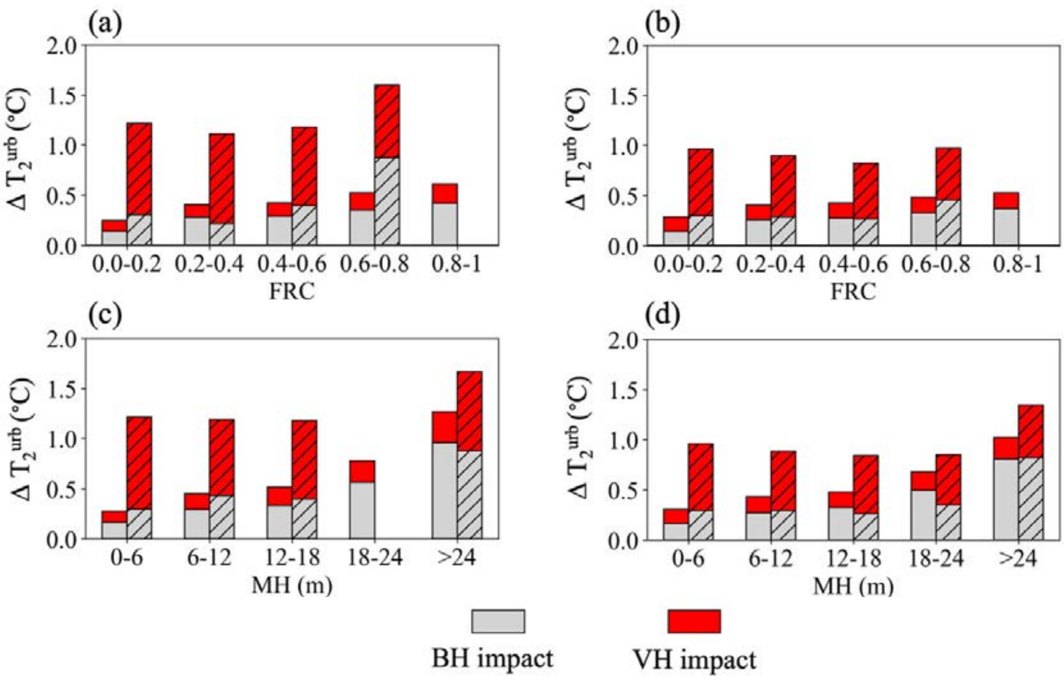

Figure 5. Relative impact of vehicle heat to building heat on ΔT2urb over different ranges of (a) and (b) urban area fraction (FRC); (c) and (d) mean building height (MH) during (left) 8 am – 10 am and (right) 11 pm – 1 am in summer. Clear bars are results over the entire land area, and shaded bars denote the results over areas with vehicle heat impact statistically significant at the 90% confidence level.

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