Revising the definition of anthropogenic heat flux from buildings: role of human activities and building storage heat flux

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Abstract. Buildings are a major source of anthropogenic heat emissions, impacting energy use and human health in cities. The difference in magnitude and time lag between building energy consumption and building anthropogenic heat emission is poorly quantified. Energy consumption (Q_{EC}) is a widely used proxy for the anthropogenic heat flux from buildings ($Q_{F,\mathrm{B}}$). Here we revisit the latter's definition. If $Q_{F,\mathrm{B}}$ is the heat emission to the outdoor environment from human activities within buildings, we can derive it from the changes in energy balance fluxes between occupied and unoccupied buildings. Our derivation shows the difference between Q_{EC} and $Q_{F,\mathrm{B}}$ is attributable to a change in the storage heat flux induced by human activities ($\Delta S_{\mathrm{o-uo}}$) (i.e., $Q_{F,\mathrm{B}} = Q_{EC} - \Delta S_{\mathrm{o-uo}}$). Using building energy simulations (EnergyPlus) we calculate the energy balance fluxes for a simplified isolated building (obtaining $Q_{F,\mathrm{B}}$, Q_{EC}, $\Delta S_{\mathrm{o-uo}}$) with different occupancy states. The non-negligible differences in diurnal patterns between $Q_{F,\mathrm{B}}$ and Q_{EC} are caused by thermal storage (e.g. hourly $Q_{F,\mathrm{B}}$ to Q_{EC} ratios vary between -2.72 and 5.13 within a year in Beijing, China). Negative $Q_{F,\mathrm{B}}$ can occur as human activities can reduce heat emission from a building but this is associated with a large storage heat flux. Building operations (e.g., opening windows, use of space heating and cooling system) modify the $Q_{F,\mathrm{B}}$ by affecting not only Q_{EC} but also the $\Delta S_{\mathrm{o-uo}}$ diurnal profile. Air temperature and solar radiation are critical meteorological factors explaining day-to-day variability of $Q_{F,\mathrm{B}}$. Our new approach could be used to provide data for future parameterisations of both anthropogenic heat flux and storage heat fluxes from buildings. It is evident that storage heat fluxes in cities could also be impacted by occupant behaviour.

1 Introduction

Human's activities that influence energy exchanges are critical to a wide variety of disciplines (e.g. meteorology, building design, geography, climatology, hydrology, engineering). As disciplines often have interests in different scales, purposes and/or boundary conditions, the terminology and acceptable assumptions differ. However, disciplines may provide data to each other or help improve assumptions used. In this study we are concerned with the interface between meteorology, climatology and building design in urban areas.

To model the weather and climate in urban areas, an important additional source of energy to the environment is the anthropogenic heat flux (Q_F). This is defined as the heat converted from consumption of biological, chemical and electrical energy and released to the atmosphere due to human activities (Oke et al., 2017). Q_F has three major sources, including metabolic (people and animals) activities ($Q_{F,\mathrm{M}}$), transport ($Q_{F,\mathrm{T}}$) and buildings ($Q_{F,\mathrm{B}}$) (Grimmond, 1992). It can be large relative to incoming solar radiation in summer (e.g. 43% in an area of Beijing (Nie et al., 2014)) and increases air temperature in cities (e.g.(Ichinose et al., 1999; Fan and Sailor, 2005)), subsequently contributing to higher cooling demand for buildings (Santamouris et al., 2001; Takane et al., 2019). In winter Q_F can contribute to the intensity of the urban heat island (Biggart et al., 2021). Not all heat generated within the building volume is directly ejected into the outdoor environment immediately but subject to change in magnitude and time lag. For example, the heat generated from human activities inside buildings is released initially indoors (via heating or cooling application), then transported through the building fabric by conduction, allowing it to be transported into atmosphere by turbulent sensible heat flux and outgoing longwave radiation. In this process the net storage heat flux (ΔQ_S) of building is modified since building fabric temperature is changed by absorbing more heat from the internal heat generation.

In urban areas, ΔQ_S is the net uptake or release of energy from urban volume. This term is an important determinant of urban climate and is regarded as a key process in the genesis of urban heat island (Goward, 1981). The change in building ΔQ_S is modified when heat is released by human activities but the timing of the externally emissions are impacted by the building fabric characteristics and the conduction process. As prior studies often use energy consumption (Q_{EC}) as a proxy for $Q_{F,\mathrm{B}}$, derived from inventory related approaches (e.g. Sailor and Lu, 2004; Iamarino et al., 2012) and building energy modelling (e.g. Heiple and Sailor, 2008; Nie et al., 2014) , the impact on ΔQ_S is not addressed. To qualify the 'real' $Q_{F,\mathrm{B}}$ and change of ΔQ_S, we revisit the definition of $Q_{F,\mathrm{B}}$ and attempt to understand how human activities affect the energy balance fluxes of buildings.

If $Q_{F,\mathrm{B}}$ is the heat released from buildings into the atmosphere as a result of human activities inside the building (including human metabolism), when the building is completely unoccupied (e.g. no operational appliances, no people: such as 'ghost cities' in China (Shepard, 2015) or vacant in Dublin (Kelly and Scott, 2018)); then $Q_{F,\mathrm{B}}$ is zero. However, heat released from the unoccupied building is non-zero as there is still heat exchange between building and ambient environment (see Eq. 1 and 2), as occurs in other environments with large mass, such as forests (e.g. Oliphant et al., 2004), and rocks (e.g. Wang et al., 2018). $Q_{F,\mathrm{B}}$ differs from building heat emission (BHE) (e.g., Hong et al., 2020; Ferrando et al., 2021) as the latter is the total heat flux released from buildings to the ambient air ($BHE_{\text{uo}} = Q_{H,\text{uo}} + Q_{BAE,\text{uo}} + L_{\downarrow,\text{uo}[air\rightarrow boi]} - L_{\uparrow,\text{uo}[boi\rightarrow air]}$) not due to human activities alone. Shortwave and longwave radiation can enter the unoccupied internal building space through windows and conduction through walls. It modifies the heat stored within the building volume and the temperature of the building envelope and indoor air, subsequently influencing the emission of heat via sensible heat flux, outgoing longwave radiation and air exchange. But this energy leaving the unoccupied building is not anthropogenic heat flux. For an occupied building, the internal heat gain arises from:

(1) the equivalent sources and sinks as the unoccupied buildings; but also

(2) the energy linked to the indoor human activities (metabolism, powered appliances and energy inputs to heating or cooling).

These will modify each of the energy balance fluxes. Some of this additional energy is transported out of buildings through indoor-outdoor ventilation exchange and/or HVAC system, immediately contributes to $Q_{F,\text{B}}$, while some is stored in the building fabric, and later is released outdoors through various pathways (convection, radiation, conduction) to become $Q_{F,\text{B}}$ with a time lag. Here, we derive $Q_{F,\text{B}}$by looking at the difference of heat fluxes between occupied and unoccupied buildings.

If the energy balance for the building system (including the indoor air and building envelope) for an unoccupied dry building (assuming latent heat is not important in this case) is:

$$Q^*_{uo} = Q_{H,\text{uo}} + Q_{BAE,\text{uo}} + \Delta Q_{S,\text{uo}} \tag{1}$$

The radiation balance for an isolated unoccupied (*uo*) building can be expressed as:

$$Q^*_{\text{uo}} = K_{\downarrow,\text{uo}} - K_{\uparrow,\text{uo}} + L_{\downarrow,\text{uo}} - L_{\uparrow,\text{uo}} \tag{2}$$

where Q^* is the net all-wave radiation, K is the shortwave radiation incoming (↓) and outgoing (↑) to the external surfaces. The longwave (L) radiation exchanges depend on the view factors (F) between the building of interest (*boi*), the surrounding facets of other surfaces/buildings (*other b*) and the sky:

$$L_{\downarrow,\text{uo}} = L_{\downarrow,\text{uo}(F[sky\rightarrow boi])} + L_{\downarrow,\text{uo}(F[other\ b\rightarrow boi])} \tag{3}$$

$$L_{\uparrow,\text{uo}} = L_{\downarrow,\text{uo}(F[\text{boi}\rightarrow\text{sky}])} + L_{\uparrow,\text{uo}(F[\text{boi}\rightarrow\text{other b}])} \tag{4}$$

In Eq. (1), Q_H is the turbulent sensible heat flux (convection) from external surfaces to the external ambient air. Q_{BAE} is the net energy exchange from the buildings through air exchange (e.g. ventilation). When the building is sealed Q_{BAE} is 0 W m^{-2}, otherwise (e.g. open windows, cracks) it can be a source or sink of energy (environment ← building, or inverse). ΔQ_S is the net storage heat flux of the building volume (i.e. fabric, contents, including the air). The left-hand side (LHS) of Eq. (1) is the inputs or source of energy to the building, whereas the right-hand side (RHS) is the sink or energy dissipation outputs. With no human activities within the building and the internal heat generation from human and infrastructure activities is zero.

When the building is occupied (o) (e.g. appliances operating / people presence), additional terms are needed in Eq. (1) to account for the supply of energy into the building for these activities and the release of energy:

$$Q_{\mathrm{o}}^{*} + Q_{Internal,\mathrm{o}} + Q_{HVAC,\mathrm{o}} = Q_{H,\mathrm{o}} + Q_{BAE,\mathrm{o}} + \Delta Q_{S,\mathrm{o}} + Q_{Waste,\mathrm{o}} \tag{5}$$

The two additional sources of energy (LHS) are:

(1) $Q_{Internal,\mathrm{o}}$: energy released within the building from lighting, powered appliances and metabolism (e.g. people, pets).

(2) $Q_{HVAC,\mathrm{o}}$: energy consumption in the building from heating, ventilation and air conditioning (HVAC) system.

As the building may emit exhaust/waste heat (e.g. via HVAC systems), there is an additional sink (RHS) referred to here as $Q_{Waste,\mathrm{o}}$. The cooling system, $Q_{Waste,o}$ will remove energy from both anthropogenic (e.g. metabolism, lighting, electrical appliance and $Q_{HVAC,\mathrm{o}}$) and natural sources (e.g. solar radiation through windows, heat diffusion through building envelope). Thus, only the natural sources occur in both the occupied and unoccupied states. In a 'simple' occupied state, with HVAC operated only (i.e. no people or other appliances) there is a difference in the building storage heat flux because of the alternative route to transport this natural heat of the building out from additional source of energy.

Here Q_H only represents the convection heat transfer at building external surface (i.e. wall, roof and windows). Both $Q_{Waste,}$ and Q_{BAE} will be incorporated into the turbulent sensible heat flux by the time they reach the inertial sub-layer (ISL) or constant flux layer (CFL). Hence, sensors (e.g. eddy covariance or large aperture scintillometry) located in the ISL would observe this as Q_H. The separation of these three terms is to better understand how human activities (e.g. open/closed windows, HVAC operation) influence each heat flux. Urban canopy parameterisation (UCP) can use this information about the separate sources and their roles in the urban energy balance to account for the modified fluxes by the time they reach the ISL. Additionally, it is clearer for multi-layer UCP where vertically the energy should enter.

To determine the impact of the occupancy (i.e. not just the physical building form) we can consider the difference between Eq. (5) and Eq. (1). If the radiation balance for the occupied case is:

$$Q_{\mathrm{o}}^{*} = K_{\downarrow,\mathrm{o}} - K_{\uparrow,\mathrm{o}} + L_{\downarrow,\mathrm{o}} - L_{\uparrow,\mathrm{o}} \tag{6}$$

We assume that the incoming and outgoing shortwave radiation remains unchanged because the reflectivity, transmissivity and absorptivity do not change by occupancy activities then:

$K_{\downarrow,o} = K_{\downarrow,uo}$; $K_{\uparrow,o} = K_{\uparrow,uo}$

The incoming longwave radiation is dependent on the surroundings which are independent to the building state, so:

$L_{\downarrow,o} = L_{\downarrow,uo}$

Thus, the difference in radiative fluxes between occupied and unoccupied building ($\Delta L_{\uparrow,o-uo}$) is:

$$\Delta L_{\uparrow,\mathrm{o-uo}} = L_{\uparrow,\mathrm{o}} - L_{\uparrow,\mathrm{uo}} \tag{7}$$

Similarly, the difference of the heat transfer through air exchange is:

$$\Delta BAE_{\mathrm{o-uo}} = BAE_{\mathrm{o}} - BAE_{\mathrm{uo}} \tag{8}$$

With the additional terms in Eq. (5) and the air exchanges rates difference from the activities within the buildings, gives:

$$\Delta \mathrm{B}_{\mathrm{o-uo}} = \left[Q_{Internal,\mathrm{o}} + Q_{HVAC,\mathrm{o}}\right] - \left[\, Q_{Waste,\mathrm{o}} + \Delta \mathrm{BAE}_{\mathrm{o-uo}}\right] \tag{9}$$

As the change in surface temperature influences the sensible heat fluxes and storage heat fluxes:

$$\Delta H_{\mathrm{o-uo}} = H_{\mathrm{o}} - H_{\mathrm{uo}} \tag{10}$$

$$\Delta S_{\mathrm{o-uo}} = \Delta Q_{S,\mathrm{o}} - \Delta Q_{S,\mathrm{uo}} \tag{11}$$

By combining the Eq. (1) and Eq. (5), we obtain:

$$\Delta B_{\mathrm{o-uo}} = \Delta L_{\uparrow,\mathrm{o-uo}} + \Delta H_{\mathrm{o-uo}} + \Delta S_{\mathrm{o-uo}} \tag{12}$$

where the LHS accounts for the net available energy as result of human activities in indoor environments and the RHS shows that these impact the longwave radiation, turbulent sensible and storage heat fluxes (in this dry case). With rearrangement:

$$\left[Q_{Internal,\mathrm{o}} + Q_{HVAC,\mathrm{o}}\right] = \Delta S_{\mathrm{o-uo}} + \left[\Delta L_{\uparrow,\mathrm{o-uo}} + \Delta H_{\mathrm{o-uo}} + \Delta BAE_{\mathrm{o-uo}} + Q_{Waste,\mathrm{o}}\right] \tag{13}$$

The additional energy generation associated with human activities to the whole building system (LHS) is apparent, as traditionally defined as $Q_{F,\mathrm{B}}$ previously (Heiple and Sailor, 2008). Here because the heat release from human metabolism indoors is considerably smaller than other sources, for simplicity of analysis, we assume metabolic heat is also part of energy consumption ($Q_{EC} = Q_{Internal,\mathrm{o}} + Q_{HVAC,\mathrm{o}}$). Besides, some of additional energy is associated with the extra gain or release of stored heat within the building volume ($\Delta S_{\mathrm{o-uo}}$). The rest is the heat released to outdoor environment from building due to human activities, which is the $Q_{F,\mathrm{B}}$ based on its definition:

$$Q_{F,\mathrm{B}} = \Delta L_{\uparrow,\mathrm{o-uo}} + \Delta H_{\mathrm{o-uo}} + \Delta BAE_{\mathrm{o-uo}} + Q_{Waste,\mathrm{o}} \tag{14}$$

Eq. (14) demonstrates the $Q_{F,\mathrm{B}}$ is the relative heat emission at exterior building boundary between unoccupied and occupied building through longwave radiation, convection, air exchange and waste heat from any mechanical heating/cooling system. The source of $Q_{F,\mathrm{B}}$ within the building volume gives (by combining Eq. (13) and Eq. (14):

$$Q_{F,\mathrm{B}} = Q_{EC} - \Delta S_{\mathrm{o-uo}} \quad (15)$$

The sources of $Q_{F,\mathrm{B}}$ are from both energy consumption (Q_{EC}) and difference of storage heat flux ($\Delta S_{\mathrm{o-uo}}$) between unoccupied and occupied building ($Q_{F,\mathrm{B}}$ in this study includes part of $Q_{F,\mathrm{M}}$ from human metabolism). In most prior studies, the second term of Eq. (15) is ignored. Although the storage heat flux over a year should tend to zero, over short periods (e.g. sub-daily) $\Delta S_{\mathrm{o-uo}}$ is not zero causing time lag and magnitude difference between $Q_{F,\mathrm{B}}$ and Q_{EC}. Therefore, estimation of $Q_{F,\mathrm{B}}$ by differences in heat emission between occupied and unoccupied buildings can capture the impact of dynamic changes in the building storage heat flux especially at sub-annual temporal cycle.

In this study, the objective is to understand the temporal profile of $Q_{F,\mathrm{B}}$, and how and why it differs from Q_{EC} at diurnal and seasonal time scales, by examining differences in energy balance fluxes between an occupied and unoccupied same building. A building energy simulation tool (EnergyPlus) is used to obtain the various energy balance fluxes from the building system.

2 Methods

2.1 Unoccupied (uo) and occupied (o) building energy simulation (BES)

Building energy simulation (BES) is widely used to estimate energy consumption, heat emission and heat storage within a building, while allowing changes in heat fluxes due to human activities to be estimated. Here we use EnergyPlus version 9.4 (DOE, 2020) to study an isolated building (i.e. without a surrounding neighbourhood). The ASNI/ASHRAE standard 140 Case 900 test model (ASHRAE, 2017) is used, which is developed in a software-to-software comparative tests for validating building thermal load. It is a 48 m^2 one-story heavyweight rectangular prism with high mass fabrics (Appendix A), whose simple geometry is ideal to understand the process of how human activities change the building energy balance fluxes in a theoretical study. Modifications of the original building model for this study, include: windows are reduced to one (6 m^2 south-facing) for more appropriate EnergyPlus single-sided ventilation calculations (Daish et al., 2016); and internal heat gain, ventilation control strategy and HVAC system operation vary with different scenarios considered (Table 1). For the simulations, the building is assumed to be located in Beijing as the climate has both hot summer and cold winter conditions. Chinese Standard Weather Data (CSWD) selected to create a Typical

Meteorological Year (TMY) (China Meteorological Bureau et al., 2005) are used as the meteorological forcing, as these data are developed for simulating building thermal load and energy use.

The modelling scenarios (Table 1) vary with building occupation state. Two types of unoccupied (*uo*) buildings are considered. Neither have internal heat gains nor HVAC systems, but they differ based on air exchange between (1) unoccupied sealed (*us*) with no infiltration or ventilation, and (2) unoccupied ventilated (*uv*) with 50% of windows area kept open. The single-sided natural ventilation rate is estimated by including both wind-driven ventilation rate (V_W, m^3 s^{-1}) (Warren 1977):

$$V_W = 0.025 A_{eff} U_W \quad (16)$$

and the stack buoyancy-driven ventilation rate (V, m^3 s^{-1}) (Warren 1977):

$$V_{Stack} = \frac{1}{3} A_{eff} C_d \sqrt{\frac{\Delta T H g}{T_{ave}}} \quad (17)$$

where A_{eff} is the effective opening area (m^2), U_W is reference wind speed at the height of opening (m s^{-1}). C_d is discharge coefficient (usually taken as 0.6 (Wang and Chen, 2012)), ΔT is indoor and outdoor air temperature difference (°C), *H* is the height of opening (m), *g* the gravitational acceleration (m s^{-2}), T_{ave} is average indoor and outdoor air temperature (°C). The combined ventilation rate is (Fan et al., 2021):

$$V_T = \sqrt{V_W^2 + V_{Stack}^2} \quad (18)$$

The three occupied (*o*) building simulations assume occupant behaviour modifies internal heat generation, natural ventilation and HVAC systems (*ov*). First, *ov1* has internal heat gains ($Q_{Internal,\mathrm{o}}$) from human metabolism, lighting and other appliances based on local building code (MOHURD, 2018), with window always open (50%, as *uv*). The internal heat gains are held constant allowing the fraction of heat in $Q_{F,\mathrm{B}}$ and ΔQ_S to be impacted by building and climate conditions but not the diurnal variability of human heat generation.

Second, *ov2* considers natural ventilation based on passive cooling and thermal comfort. The window opening is controlled automatically. It is opened (50% of window area) when the indoor air temperature is higher than both outdoor air temperature and ventilation setpoint (23°C for 'warm limit' in bedroom (Oikonomou et al., 2012)). Otherwise, it is closed to reduce heat loss and keep the building warm. Third, since natural ventilation alone may not satisfy indoor thermal comfort, mixed mode ventilation with auxiliary HVAC system (e.g. Wang and Chen, 2013; Wang and Greenberg, 2015; Chen et al., 2017) is considered in *ov3*. The mechanical heating and cooling system are active when indoor temperature reaches the threshold (18°C for heating and 26°C for cooling, MOHURD, 2018). The ventilation control strategy in *ov3* is the same as *ov2,* but the EnergyPlus hybrid ventilation manager (DOE, 2020) turns the HVAC off when natural ventilation is active to prevent simultaneous operation.

Table 1. Cases simulated differ based on building occupation state, internal heat gain ($Q_{Internal,\mathrm{o}}$) and presence of natural ventilation and HVAC. Notation are defined in text and nomenclature

Code	Occupation state	Natural ventilation	$Q_{Internal,\mathrm{o}}$ (W m^{-2})	Window open Temperature control (°C)	HVAC Heating/ cooling setpoint (°C)
us	uo	Sealed	0	N/A	N/A
uv	uo	Window always open (50%)	0	N/A	N/A
ov1	o	Window always open (50%)	11.8	N/A	N/A
ov2	o	Controlled ventilation	11.8	23	N/A
ov3	o	Mixed mode control	11.8	23	18/26

2.2 Determination of anthropogenic heat flux

The simulated hourly heat fluxes by radiation, convection, air exchange and waste heat generated from HVAC system between the isolated building and atmosphere (Table A.3) are analysed for each case (Table 2). If cooling occurs, the waste heat consists of the cooling load and electrical energy consumed by the air conditioner (Q_{HVAC}). Q_{HVAC} is predicted using a static coefficient of performance (COP) for the air conditioner, and the heat removed by an air conditioner (Q_{AC}) to the total amount of electricity consumed:

$$Q_{HVAC,C} = \frac{Q_{AC}}{COP} \quad (19)$$

$$Q_{Waste,C} = Q_{AC}(1 + \mathrm{COP}^{-1}) \quad (20)$$

With a centralised heating system (as Beijing has), for simplicity we assume all energy associated with the heating system is released indoors, and waste heat due to boiler efficiency and pipe heat loss are not considered:

$$Q_{HVAC,H} = Q_{HS} \quad (21)$$

$$Q_{Waste,H} = 0 \quad (22)$$

Combining mechanical heating and cooling, the energy consumption and corresponding waste heat from HVAC system gives:

$$Q_{HVAC} = Q_{HVAC,\mathrm{C}} + Q_{HVAC,\mathrm{H}} = \frac{Q_{AC}}{COP} + Q_{HS} \quad (23)$$

$$Q_{Waste} = Q_{Waste,\mathrm{C}} + Q_{Waste,\mathrm{H}} = Q_{AC}(1 + \mathrm{COP}^{-1}) \quad (24)$$

Each term in Eq. (14) is determined using an occupied (*o*) and unoccupied (*uo*) building result to determine $Q_{F,\mathrm{B}}$ and the other fluxes. The results are analysed by season (spring (March, April and May; MAM), summer (JJA), autumn (SON) and winter (DJF)) using the median (50%) and interquartile range (IQR) between the 25$^{\mathrm{th}}$ and 75$^{\mathrm{th}}$ percentiles to assess the diurnal patterns.

2.3 Ratio of anthropogenic heat flux to energy consumption

If the energy consumed within the building is rejected immediately into the atmosphere (Heiple and Sailor, 2008), the change in ΔQ_S is not accounted for, and therefore $Q_{F,\mathrm{B}}$ is assumed to be only from energy consumption (Q_{EC}). The variation of ΔQ_S associated with human activities is considered when using the relative heat emissions in Eq. (14) and Eq. (15). We use the ratio $R = \frac{Q_{F,\mathrm{B}}}{Q_{EC}}$ to determine the relative importance of building operation modes and choice of baselines on the discrepancy between $Q_{F,\mathrm{B}}$ and Q_{EC}.

3 Results and discussion

Building energy balance fluxes vary through each day and season (Fig. 1) associated with when a building is occupied and people's activities inside the building. First, we consider one case in detail – an occupied building with both natural ventilation and HVAC (*ov3,* Table 1) relative to an unoccupied sealed building (*us,* Table 1) – their difference (*ov3-us*) allows us to obtain the fluxes needed (Sect. 1).

As noted (Sect. 1), the shortwave and incoming longwave radiative fluxes for all cases (Table 1) are assumed identical, but all other terms of the building energy balance differ. Hence, the change in outgoing longwave radiation ($\Delta L_{\uparrow,\mathrm{o-uo}}$, Fig. 1c) is equivalent to the net all-wave radiation difference ($Q^{*}_{\mathrm{o-uo}}$, Fig. 1a-b) for the occupied and unoccupied buildings. The positive sensible heat flux difference (Eq. (10), $\Delta H_{\mathrm{o-uo}}$, Fig. 1c) and $\Delta L_{\uparrow,\mathrm{o-uo}}$ indicate the building is warmed up by internal heat gains ($Q_{Internal,\mathrm{o}}$) with higher exterior surface temperatures. Their small magnitudes and flat patterns indicate small relative importance compared to the heat exchange from ventilation differences (Eq. (8), $\Delta BAE_{\mathrm{o-uo}}$, Fig. 1c). The latter, not only contributes the largest fraction of anthropogenic heat flux ($Q_{F,\mathrm{B}}$, Fig. 1c), but also has a diurnal pattern consistent with $Q_{F,\mathrm{B}}$, especially during spring and autumn (Fig. 1c, i). Rarely, heat ($Q_{Waste,\mathrm{o}}$, Fig. 1i) is emitted by the air conditioner in the mid-afternoon (shading) at this time of year, but more importantly in summer (Fig. 1f) when cooling demand increases.

$Q_{F,\mathrm{B}}$ (Eq. (14), Fig. 1c) has four components of emitted heat, whereas energy consumption (Q_{EC}, Fig. 1c) only has (in this case, constant) internal heat gains ($Q_{Internal,\mathrm{o}} = 11.8$ W m^{-2}, Fig. 1b, Table 1) and energy use from HVAC system (Q_{HVAC}, Fig. 1b). Their difference is the storage heat flux difference (Eq. (15) $\Delta S_{\mathrm{o-uo}}$ in Fig. 1c). If $\Delta S_{\mathrm{o-uo}}$ is positive, the building acts as a heat sink and stores the extra heat generated by human activities, or stored heat is released when $\Delta S_{\mathrm{o-uo}}$ is negative. Hence, we can identify the impacts of seasonal-varying human activities and building operations on the diurnal variability in $\Delta S_{\mathrm{o-uo}}$, Q_{EC} and $Q_{F,\mathrm{B}}$.

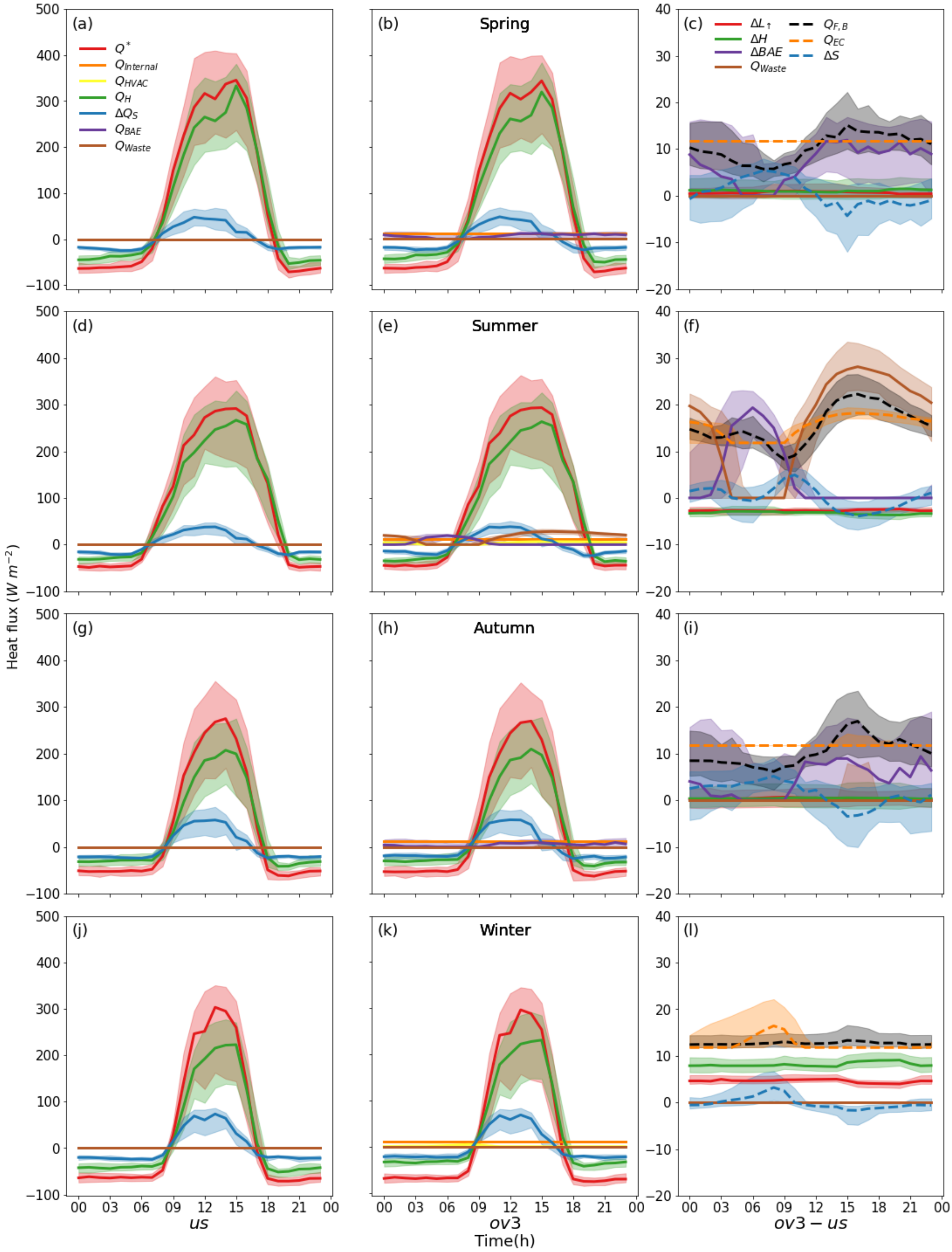

Figure 1: Seasonal diurnal median (line) and inter-quantile range (IQR, shading) building heat fluxes for (a, d, g, j) unoccupied sealed (us), (b, e, h, k) occupied ventilated (*ov3*) building and their (c, f, i, l) difference (*ov3-us*) for (a-c) spring, (d-f) summer, (g-i) autumn and (j-l) winter. $\boldsymbol{Q_{F,B}}$ is estimated by either heat transfer difference (solid line components): $\boldsymbol{Q_{F,B}} = \Delta \boldsymbol{L}_{\uparrow,\mathbf{o-uo}} + \Delta \boldsymbol{H}_{\mathbf{o-uo}} + \Delta \boldsymbol{BAE}_{\mathbf{o-uo}} + \boldsymbol{Q_{Waste,o}}$ in Eq. (14) or energy consumption and storage flux difference: $\boldsymbol{Q_{F,B}} = \boldsymbol{Q_{EC}} - \Delta \boldsymbol{S}_{\boldsymbol{o-uo}}$ (dash line components) in Eq. (15)

3.1 Impact of human activities on seasonal and diurnal variations of the fluxes

For the same *ov3-us* case (Table 1, Fig. 1), we consider the diurnal and seasonal variability of the fluxes. In spring and autumn (Fig. 1a-c, g-i), natural ventilation is the dominant factor contributing to diurnal variation in $\Delta S_{\mathrm{o-uo}}$ and $Q_{F,\mathrm{B}}$, while Q_{EC} has minimal variability. Q_{EC} is slightly larger than $Q_{Internal,\mathrm{o}}$ because of some short periods of HVAC use in the mid-afternoon (IQR shading in Fig. 1i). There is a clear diurnal cycle of $Q_{F,\mathrm{B}}$ (Fig. 1c) with the median varying between 8 W m^{-2} (07:00) and 15 W m^{-2} (15:00) relative to the constant internal heat gain (11.8 W m^{-2}). The difference between $Q_{F,\mathrm{B}}$ and Q_{EC} ($\Delta S_{\mathrm{o-uo}}$) is largely impacted by natural ventilation. During the night and early morning with closed window, only part of the consumed energy is transferred externally to the atmosphere. The rest of the heat is stored in the building fabric (positive $\Delta S_{\mathrm{o-uo}}$), hence $Q_{F,\mathrm{B}}$ is lower than Q_{EC}. However, when overheating may occur during the middle of the day, occupants keep window opened (air conditioner is less frequently used) to cool the building down, with stored heat released (negative $\Delta S_{\mathrm{o-uo}}$). This is consistent with the diurnal variability of $\Delta BAE_{\mathrm{o-uo}}$, which has a minimum at night (window closed) and maximum in the mid-noon (window open).

In summer, the daytime natural ventilation is replaced by air conditioning as natural ventilation alone could not maintain thermal comfort indoors. Natural ventilation and waste heat from the air conditioner ($Q_{Waste,\mathrm{o}}$) contribute to one peak $Q_{F,\mathrm{B}}$ at nighttime and daytime, respectively (Fig. 1f). $Q_{F,\mathrm{B}}$ is higher than Q_{EC} around these two peak periods (05:00-07:00 and 13:00-21:00). The peak $Q_{F,\mathrm{B}}$ at night reaches 14 W m^{-2} (median) at 05:00, which is mainly attributed to natural ventilation when outdoor air temperature is cooler than indoors. Conversely, in the afternoon when outdoor temperature is warmer, occupants 'choose' mechanical cooling for achieving thermal comfort. The peak $Q_{F,\mathrm{B}}$ is 22 W m^{-2} at 16:00, approximately 22% higher than Q_{EC} . It indicates that using Q_{EC} for the anthropogenic heat flux from buildings (e.g. Heiple and Sailor, 2008) may underestimate the effect of $Q_{F,\mathrm{B}}$ on urban atmospheric processes especially during the late afternoon/early evening. In addition, $Q_{F,\mathrm{B}}$ is always smaller than $Q_{Waste,\mathrm{o}}$ because of the negative $\Delta L_{\uparrow,\mathrm{o-uo}}$ and $\Delta H_{\mathrm{o-uo}}$ causing a cooler exterior surface. This suggests using $Q_{Waste,\mathrm{o}}$ as $Q_{F,\mathrm{B}}$ (e.g. Chow et al., 2014) may overestimate $Q_{F,\mathrm{B}}$ in summer.

However, in winter, mechanical heating and thermal mass effect shape the temporal pattern of $Q_{F,\mathrm{B}}$ (Fig. 1i). The cool outdoor air temperature before sunrise results in a substantial heating supply and peak Q_{EC} (16.43 W m^{-2} for median line) at 08:00. This heat is stored in building fabric (positive $\Delta S_{\mathrm{o-uo}}$) and have a relatively stable release through convection and longwave radiation. Therefore the diurnal profile $Q_{F,\mathrm{B}}$ is rather flatter and $\Delta S_{\mathrm{o-uo}}$ has a highly consistent temporal pattern to Q_{EC}.

Overall, this analysis recognizes the crucial role of $\Delta S_{\mathrm{o-uo}}$in distinguishing $Q_{F,\mathrm{B}}$ from Q_{EC}, which is highly dependent on HVAC operation and natural ventilation (i.e., human activity of window opening). These two factors can rapidly increase or decrease $Q_{F,\mathrm{B}}$ while convection and longwave radiation cannot. Whereas in winter, the larger IQR (shading) of $Q_{F,\mathrm{B}}$ than Q_{EC} indicates more day-to-day variation in $Q_{F,\mathrm{B}}$ diurnal profile than Q_{EC}. Estimates of $Q_{F,\mathrm{B}}$ using satellite remote sensing found heat storage plays an important role in moderating energy use within buildings (Yu et al., 2021). As the storage heat flux change modifies the diurnal sensible heat flux pattern it modifies the surface temperature increment ($Q_{F,\mathrm{B}}$ in remote sensing approach) and hence the apparent energy consumption.

The diurnal profiles of $\Delta S_{\mathrm{o-uo}}$are not identical between seasons as people use different actions to achieve thermal comfort in different weather conditions. This suggests the $Q_{F,\mathrm{B}}$ and Q_{EC} differences may vary between climates and with cultural practices. In inventory methods the diurnal profiles may be limited (e.g. LUCY (Allen et al., 2011), weekday/weekend by country) and ignore seasonal variations. However, $\Delta S_{\mathrm{o-uo}}$behaviour types classes may benefit from distinguishing diurnal variation for different climates.

3.2 Impact of different building operation modes on seasonal and diurnal variations

Fig. 2 illustrates the impact of different building operation modes (Table 1: *ov1*, *ov2, ov3;* cf. *us)* on the $Q_{F,\mathrm{B}}$ diurnal profiles. It suggests the different ventilation strategies and HVAC systems do change $Q_{F,\mathrm{B}}$ in both temporal pattern and magnitude, but their impacts vary among seasons.

In spring and autumn, different natural ventilation control strategies completely modify the $Q_{F,\mathrm{B}}$ diurnal profile, whereas HVAC system only increases the peak $Q_{F,\mathrm{B}}$ slightly in autumn (Fig. 2i). The distinctly different (opposite) trend in diurnal $Q_{F,\mathrm{B}}$ pattern for *ov1* cf. *ov2* or *ov3* (Fig. 2a-c, g-i) is largely explained by the diurnal change of $\Delta BAE_{\mathrm{o-uo}}$ in the three cases. In *ov1* (window open, no control) the minimum outdoor air temperature before sunrise creates the maximum indoor and outdoor air temperature difference, therefore the highest $\Delta BAE_{\mathrm{o-uo}}$ and peak $Q_{F,\mathrm{B}}$ at 06:00 (30 W m^{-2} for the median in Fig. 2a). Whereas *ov2* and *ov3* have the window closed at night and early morning to avoid overcooling, therefore the minimum $Q_{F,\mathrm{B}}$ in the early morning (07:00). As outdoor air temperature increases through the day, $Q_{F,\mathrm{B}}$ follows the reduced $\Delta BAE_{\mathrm{o-uo}}$ in *ov1*, whereas natural ventilation is active in *ov2* and *ov3*, leading to an increase in $\Delta BAE_{\mathrm{o-uo}}$ and $Q_{F,\mathrm{B}}$. Unlike *ov2*, *ov3* has a clear peak (16 W m^{-2} median, Fig. 2i) at 15:00, because when natural ventilation alone cannot satisfy thermal comfort and *ov3* air conditioning is activated. But their overall patterns (IQR) are very consistent, indicating afternoon use of air conditioning could increase $Q_{F,\mathrm{B}}$ magnitude but have a limited impact on other parts of the diurnal pattern. Surprisingly, negative $Q_{F,\mathrm{B}}$ occurs around 17:00 in spring (Fig. 2a), suggesting the occupied building has less heat emissions than unoccupied building. Because the natural ventilation at night and morning cools down the building and reduced fabric exterior surface temperature leads to a large reduction in longwave radiation and convection ($\Delta L_{\uparrow,\mathrm{o-uo}}$and $\Delta H_{\mathrm{o-uo}}$) than increase in heat emission through natural ventilation ($\Delta BAE_{\mathrm{o-uo}}$) in afternoon. And the reduced overall emissions are converted into increase in storage heat flux ($\Delta S_{\mathrm{o-uo}}$). Negative $Q_{F,\mathrm{B}}$ also occurs when unoccupied building is always ventilated (*uv*) and occupied building is ventilated with control (*ov2* and *ov3*) in spring (e.g. Fig. B6b-c). The window is closed to avoid excessive cooling at night in *ov2*. With $\Delta BAE_{\mathrm{o-uo}}$ negative in this case, its magnitude is much larger than increase in longwave radiation and convection ($\Delta L_{\uparrow,\mathrm{o-uo}}$and $\Delta H_{\mathrm{o-uo}}$). The minimum $Q_{F,\mathrm{B}}$ frequently corresponds to the peak $\Delta S_{\mathrm{o-uo}}$.

In summer, *ov2* window is open most of the time (as in *ov1*) for thermal comfort, therefore the $Q_{F,\mathrm{B}}$ has no apparent difference to *ov1*. However for *ov3*, as air conditioning runs from morning to late night and there is a very different diurnal profile (cf. *ov2* and *ov1*). Air conditioner use contributes to a much larger $Q_{F,\mathrm{B}}$ (cf. *ov2*) from 12:00 to 21:00. Not only is extra energy consumed, but it also removes heat from building to the atmosphere in this period. In contrast, using natural ventilation as a cooling strategy (*ov1* and *ov2*) contributes to a high $Q_{F,\mathrm{B}}$ at night and early morning but very low even negative extra heat emission in afternoon. This implies natural ventilation as passive cooling strategy not only could improve the thermal conditions indoors, but also could contribute to the improvement of outdoor climate by modifying the diurnal pattern of anthropogonic heat emissions (Duan et al., 2019).

Consistent with results in the other seasons, different ventilation control strategies in winter cause a large change in $Q_{F,\mathrm{B}}$ profile between *ov1* and *ov2*. However, the temporal pattern of $Q_{F,\mathrm{B}}$ (IQR) in *ov2* is quite similar to *ov3* because the supplied heat from mechanical heating system does not immediately enhance $Q_{F,\mathrm{B}}$ with closed window. *Ov2* is the only scenario that has similar $Q_{F,\mathrm{B}}$ and Q_{EC} through the whole day. Comparison using an unoccupied ventilated (*uv)* baseline (Fig. B.6) (cf. *Us* Fig. 2) show that although $Q_{F,\mathrm{B}}$ profiles differ, the impacts of different building operation modes are consistent when the same occupied buildings used. The impact of baselines with different air exchange on $Q_{F,\mathrm{B}}$ are analysed in Sect. 3.3.

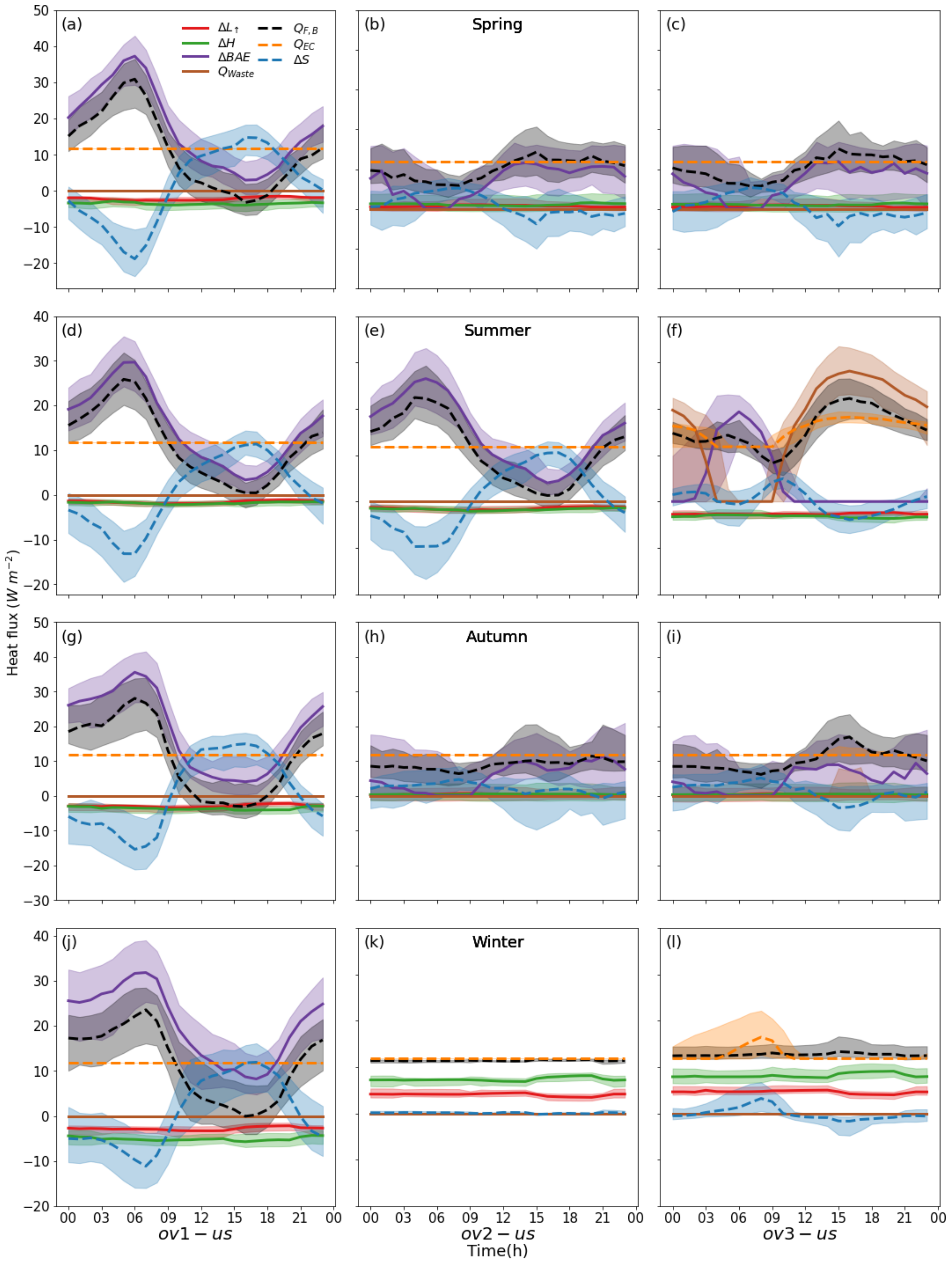

Figure 2 : As Figure 1c, f, i, j , but comparing three different building operation types (a, d, g, j) *ov1*: window is always open without control, no HVAC; (b, e, h, k) *ov2*: controlled natural ventilation for indoor thermal comfort, no HVAC; (c, f, i, l) *ov3*: mixed mode ventilation

3.3 Impact of unoccupied baseline chosen

Here two unoccupied baselines (*us* – unoccupied sealed building, *uv* – unoccupied ventilated building with uncontrolled open window) are used to assess the impact. A ratio between $Q_{F,\mathrm{B}}$ to Q_{EC} I is used (Fig. 3) to normalize the impact of baselines on their difference with different building operation modes. The largest difference in *R* occurs on 23 December at 11:00, with values of 5.13 (*ov3-uv*) and -2.72 (*ov1-us*), reflecting the considerable difference between $Q_{F,\mathrm{B}}$ to Q_{EC}.

Two diurnal patterns of the *R* ratio are distinguished. When the window is always open (*ov1* in all seasons, *ov2* in summer), $R > 1$ ($Q_{F,\mathrm{B}} > Q_{EC}$) at night/early morning (22:00-08:00), reaching its maximum around 05:00-07:00 (near sunrise in all seasons). For the remaining periods, which are relatively warm, *R* < 1. Whereas, when window opening/closing is controlled and HVAC is used for thermal comfort an almost inverse temporal pattern of R occurs, with R > 1 during afternoon when either window is open or the air conditioner is activated. The peak *R* occurs at 15:00 when both outdoor temperature and solar radiation are high.

When different unoccupied baselines are used, the temporal patterns of *R* are similar for all cases, but their magnitudes differ significantly. *R* is close to 1 when window states between unoccupied and occupied buildings are similar (e.g. *ov1-uv* in all seasons, *ov2-uv* in summer). Hence, greater difference occurs in heat transfer from ventilation or mechanical heating/cooling between occupied and unoccupied building (i.e., larger *R*). Thus, the baseline chosen impacts the results and require appropriate consideration for incorporating $Q_{F,\mathrm{B}}$ into atmospheric modelling.

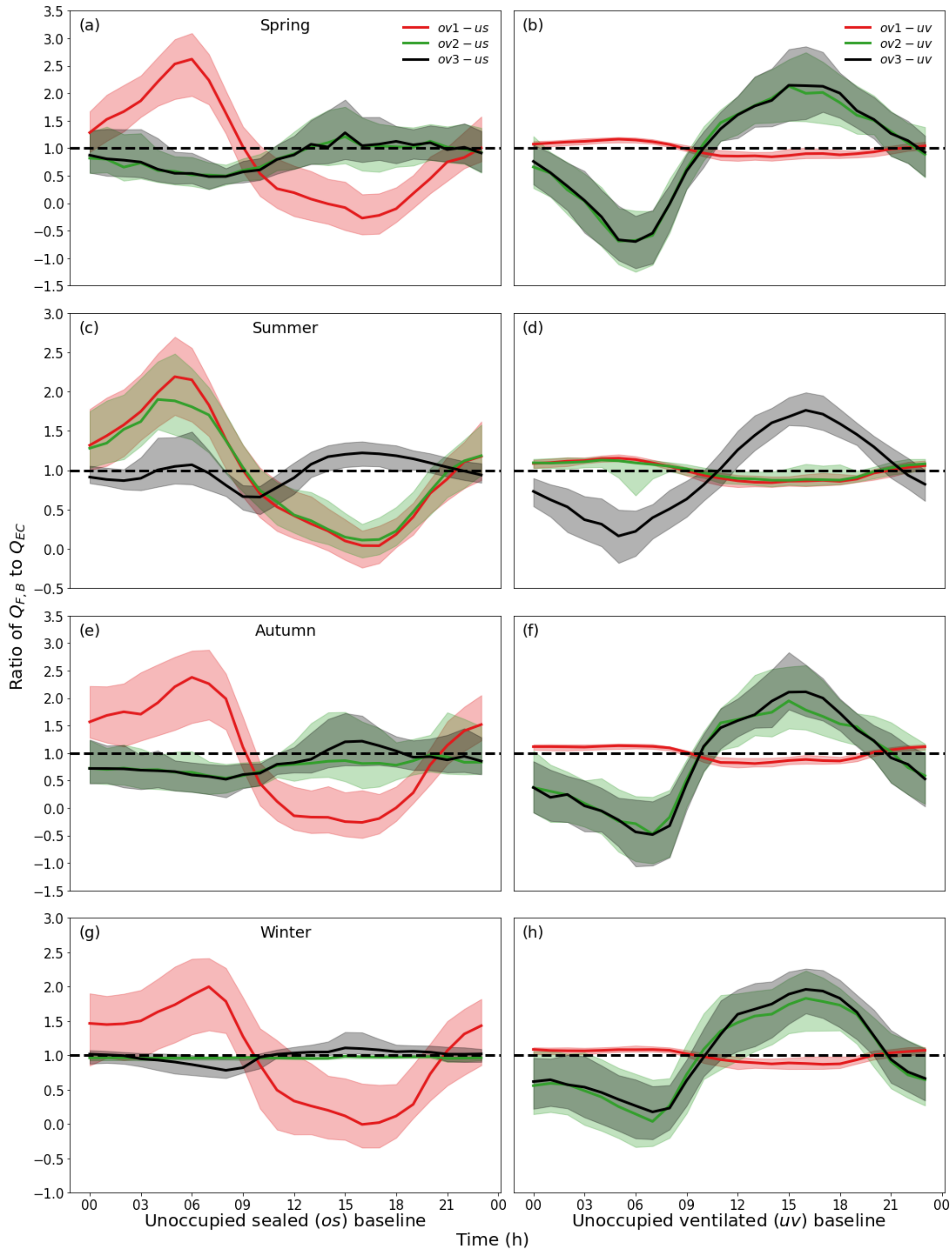

Figure 3: $Q_{F,\mathrm{B}}$ to Q_{EC} ratio I median (line) and IQR (shading) for (a-b) spring, (c-d) summer, (e-f) autumn and (g-h) winter, using two unoccupied baselines: (a, c ,e, g) sealed (*us*), and (b, d, f, h) ventilation (*uv*); each with three occupancy types (colour): *ov1*: Only internal heat gains are applied and window is fully open; *ov2*: Internal heat gains and natural ventilation control are applied. *Ov3*: Internal heat gains, natural ventilation control and HVAC system are applied. Ratio *R*=1 (Black dotted line)

3.4 Comparison between $Q_{F,\mathrm{B}}$ and building heat emission (BHM)

Comparison of building heat emissions (BHE), determined using the Hong et al. (2021) approach, to $Q_{F,\mathrm{B}}$ (this study) for one case (*ov3-us*) shows that the former is much larger than $Q_{F,\mathrm{B}}$ during the day but smaller at night and have different diurnal patterns (Fig. 4). Convection from the exterior envelope (Q_H, Figure 1b, e, h, k) is the main contributor to BHE, therefore influences the BHE diurnal profile in each season. During the day, solar radiation is large and a major control whereas $Q_{F,\mathrm{B}}$ is relatively small and consistent but modified by building-human interactions (e.g., opening windows, activation of mechanical heating and cooling systems). In this scenario shown, natural ventilation and mechanical cooling dominate $Q_{F,\mathrm{B}}$ in summer and shoulder season; while in winter in their absence, convection and longwave radiation are more important.

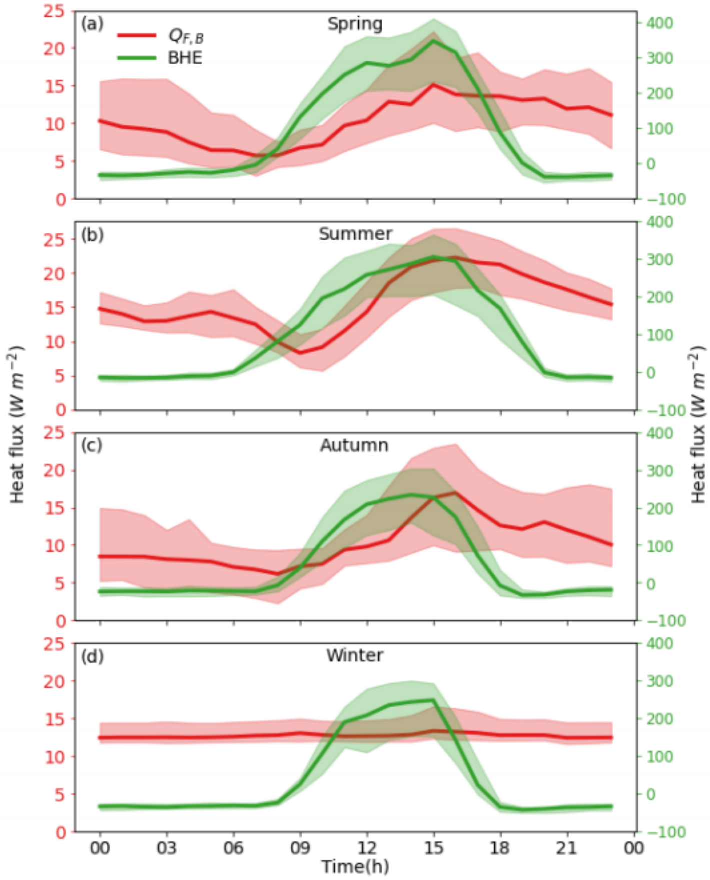

Figure 4: Comparison of seasonal diurnal $Q_{F,\mathrm{B}}$ (*ov3-us*) and building heat emission (BHE, *ov3* in Table1) for (a) spring, (b) summer, (c) autumn and (d) winter.

3.5 Daily variation of fluxes in relation to meteorological conditions

Ambient air temperature is one of the most crucial factors controlling building energy consumption (Sailor and Vasireddy, 2006). Hence, it is often used to determine daily variability of Q_{EC} (e.g. Lindberg et al., 2013) and the resulting monthly variations (e.g. Allen et al., 2011). By accounting for $\Delta S_{\mathrm{o-uo}}$ in this study, the response of

$Q_{F,\mathrm{B}}$ to ambient air temperature may differ to previous studies. To examine this we use the *ov3-us* case to consider the relations of daily mean (unless indicated) variables of air temperature (mean) , solar radiation (daily total) and simulated available energy to the building from human activities (ΔB) with anthropogenic heat flux ($Q_{F,\mathrm{B}}$in Fig. 5a), energy consumption (Q_{EC}in Fig. 5 b) and their difference ($\Delta S_{\mathrm{o-uo}}$in Fig. 5c).The overall trends between $Q_{F,\mathrm{B}}$ and Q_{EC} to ambient air temperature are consistent, with $Q_{F,\mathrm{B}}$ and Q_{EC} smallest when temperatures are between 10-15°C. This coincides with the Nicol and Humphreys'(2002) monthly balance-point temperature of 12°C, which has been regarded as the equivalent ambient air temperature with the minimum energy use within the building (e.g. Allen et al., 2011, Koralegedara et al., 2016). As the temperature increases (decreases), Q_{EC} increases proportionally with temperature due to mechanical cooling (heating). However, in contrast to Q_{EC}, $Q_{F,\mathrm{B}}$ has a much larger variability at the same temperature caused by a large range of $\Delta S_{\mathrm{o-uo}}$ (-7.7 to 9.0 W m^{-2}), which is highly dependent on human activities on diurnal scale (Sect. 3.1)

To understand the large daily variability of $\Delta S_{\mathrm{o-uo}}$, we use ΔB (net available energy from human activities in buildings in Eq. 9) to indicate the effect of human activities (heat addition or removal) in one day. Higher ΔB (larger circles) are associated with higher $\Delta S_{\mathrm{o-uo}}$ at the same ambient air temperature, especially in winter (Fig. 5c). This is not unexpected as buildings will absorb more heat when extra internal energy is added into the building. Inversely, negative ΔB (small circles) contributes to much more heat release from heat storage (lower $\Delta S_{\mathrm{o-uo}}$ through either natural ventilation or mechanical cooling. The sign and magnitude of ΔB are linked to daily cumulative solar radiation. At the same ambient air temperature, more solar radiation enhances the need for larger heat removal or less heat addition to the building for thermal comfort, therefore leading to a smaller ΔB and lower $\Delta S_{\mathrm{o-uo}}$. Consequently, we can conclude that both ambient air temperature and cumulative solar radiation are important meteorological factors to determining $\Delta S_{\mathrm{o-uo}}$ and $Q_{F,\mathrm{B}}$.

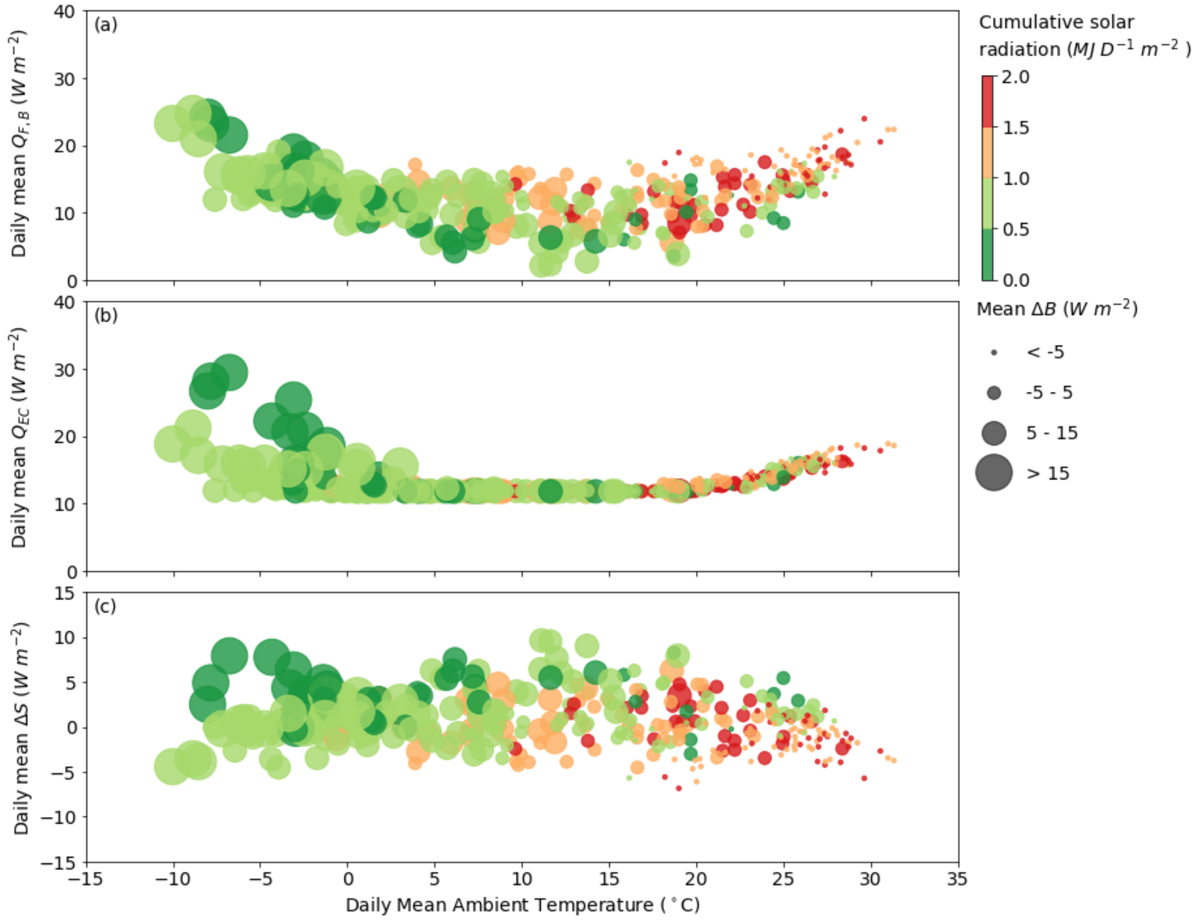

Figure 5: Daily results for the *ov3-us* case stratified by daily cumulative solar radiation (colour) and daily mean available energy to the building (size) (Eq. (9) associated with human activities, with mean external air (ambient) temperature and (a) mean anthropogenic heat flux, (b) energy consumption and (c) difference in storage heat flux.

4 Conclusions

Anthropogenic heat flux from buildings ($Q_{F,\mathrm{B}}$) is defined as the additional heat released from building into atmosphere due to human activities. It is qualitatively and quantitatively different to building energy consumption (Q_{EC}) in temporal pattern and magnitude as result of thermal inertia of building (Iamarino et al., 2012). However, as there is no standard to quantify 'real' $Q_{F,\mathrm{B}}$ most studies use Q_{EC} as a proxy via inventory and building energy modelling approaches. This paper proposes a new method to quantify a more appropriate $Q_{F,\mathrm{B}}$ by utilising the difference in heat fluxes between an occupied and unoccupied building (i.e. the built structure with absolutely no energy use and human metabolism). We show the difference between Q_{EC} and $Q_{F,\mathrm{B}}$ is attributable to a change in the storage heat flux induced by human activities ($\Delta S_{\mathrm{o-uo}}$). $Q_{F,\mathrm{B}}$ has four components based on its dissipation pathways, including outgoing longwave radiation, turbulent sensible heat flux (convection), heat release due to air exchange and waste heat from HVAC systems. We use one simplified case study in Beijing to demonstrate the analysis using building energy simulations to quantify the temporal difference between Q_{EC} and $Q_{F,\mathrm{B}}$ and understand the relative importance of building operations for thermal comfort and meteorological condition on $Q_{F,\mathrm{B}}$. The key conclusions are:

- Hourly ratios between $Q_{F,\mathrm{B}}$ and Q_{EC} can differ between -2.72 and 5.13 because of differences in occupancy use of the building (within a year, in Beijing's climate). Individual ratios frequently exceed 3 between 14:00 and 16:00 when controlled natural ventilation or mechanical cooling is activated in shoulder season). Thus, the definitions differences are large.
- Natural ventilation ($\Delta BAE_{\mathrm{o-uo}}$) or HVAC operation ($Q_{Waste,\mathrm{o}}$ for cooling and Q_{HVAC} for heating) are two predominant contributors to the storage heat flux. Hence, different building operations to control thermal comfort determine the diurnal profile of $Q_{F,\mathrm{B}}$ by affecting not only Q_{EC} but also $\Delta S_{\mathrm{o-uo}}$.
- The day-to-day variation of $Q_{F,\mathrm{B}}$ diurnal profile is broader than that of Q_{EC} .
- Diurnal profile of $\Delta S_{\mathrm{o-uo}}$ varies with season as occupants modify their behaviours and the interaction with buildings to achieve thermal comfort (e.g. cooling in summer and heating in winter), indicating differences between $Q_{F,\mathrm{B}}$ and Q_{EC} will vary with both climate and cultural norms.
- $Q_{F,\mathrm{B}}$ is sensitive to the unoccupied baseline chosen (here two are analysed unoccupied sealed vs unoccupied ventilated). An 'unoccupied baseline' needs to be integrated into urban climate modelling in the future.
- Daily mean temperature only accounts for the day-to-day variability in Q_{EC} rather than $\Delta S_{\mathrm{o-uo}}$. Both ambient air temperature and cumulative solar radiation are important meteorological factors to determine $\Delta S_{\mathrm{o-uo}}$ and $Q_{F,\mathrm{B}}$.

Our new approach should be used to provide data for future parameterisations of both anthropogenic heat flux from buildings and storage heat fluxes for urban weather and climate modelling. We conclude that storage heat fluxes in cities is also being modified by occupant behaviour, particularly by natural ventilation and mechanical cooling. It is expected that the diurnal variation of $\Delta S_{\mathrm{o-uo}}$ will vary with operation schedules for different building uses (e.g. residential vs. commercial buildings). Given the release of stored heat is critical influence on the nocturnal canopy layer urban heat island (CL-UHI), the impact of different HVAC operations on nocturnal UHI should be explored further. This is an important factor to determine diurnal pattern of $Q_{\mathrm{F,B}}$ in the shoulder season and can be expressed more accurately. However, in different climates and with different social cultural practices the periods most influenced will change. Further studies are being conducted to explore the impacts of these, while also addressing feedbacks at the neighbourhood scale.

For developers of urban canopy parameterisations (UCP) there are several considerations because of computational efficiencies essential for undertaking weather and climate modelling: (1) human activities within building are modifying both the storage heat flux and the anthropogenic heat flux; (2) assuming within an UCP that a 'simple' building energy model (BEM) (cf. a full building energy simulation scheme such as EnergyPlus) will require some human activities to be simplified, such as using fixed ventilation rate, instead of dynamic natural ventilation depending on both outdoor weather condition and thermal comfort requirements; and (3) with a multi-layer UCP the appropriate levels for the impact of these energy exchanges can be accounted for. Our current research is extending this analysis to consider moisture; and exploring the role of building materials, construction, other aspects of building design and external meteorology. The outcome of this work will also have implications for UCP development, as can help identify what can be simplified and what are critical controls in different climates and urban settings.

Data availability

All data are deposited at https://doi.org/10.5281/zenodo.5903303 (Liu et al., 2022)

Author contributions

Conceptualisation: SG and ZL, Methods and Analysis: YL SG and ZL, First draft and visualization: YL, Writing and review for submission: YL, SG and ZL Funding: SG and ZL.

Competing interests

The author declare that they have no conflict of interest.

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Nomenclature

A_{eff}	Effective area of windows opening (m^2)
ΔB_{o-uo}	Available energy to the building from human activities ($W\ m^{-2}$)
ΔBAE_{o-uo}	Difference of heat transfer by air exchange between building and atmosphere between occupied (o) and unoccupied (uo) building ($W\ m^{-2}$)
BHE	Building heat emission to ambient air ($W\ m^{-2}$)
ΔH_{o-uo}	Difference in Q_H between occupied (o) and unoccupied (uo) building ($W\ m^{-2}$)
$F_{[sky \rightarrow boi]}$	View factor from sky to building of interest
$F_{[other\ b \rightarrow boi]}$	View factor from other buildings to building of interest
$F_{[boi \rightarrow sky]}$	View factor from building of interest to sky
$F_{[boi \rightarrow other\ b]}$	View factor from building of interest to other buildings
C_d	Discharge coefficient
H	Height of windows opening (m)
$K_{\uparrow}$	Outgoing shortwave radiative flux ($W\ m^{-2}$)
$K_{\downarrow}$	Incoming shortwave radiative flux ($W\ m^{-2}$)
$L_{\uparrow}$	Outgoing longwave radiative flux ($W\ m^{-2}$)
$L_{\downarrow}$	Incoming longwave radiative flux ($W\ m^{-2}$)
$\Delta L_{\uparrow,\ o-uo}$	Difference in $L_{\uparrow}$ between occupied (o) and unoccupied (uo) building ($W\ m^{-2}$)
ΔQ_S	Net storage heat flux for the building volume ($W\ m^{-2}$)
Q^*	Net all-wave radiative flux ($W\ m^{-2}$)
Q_{AC}	Sensible cooling load from air conditioning ($W\ m^{-2}$)
Q_{BAE}	Heat transfer by air exchange between building and atmosphere ($W\ m^{-2}$)
$Q_{F,\ B}$	Anthropogenic heat flux from building sector ($W\ m^{-2}$)
$Q_{F,\ M}$	Anthropogenic heat flux from metabolic activities ($W\ m^{-2}$)
$Q_{F,\ T}$	Anthropogenic heat flux from transport ($W\ m^{-2}$)
Q_H	Turbulent sensible heat flux ($W\ m^{-2}$)
Q_{HS}	Sensible heating load ($W\ m^{-2}$)
Q_{HVAC}	Energy consumption by heating ventilation and air conditioning (HVAC) system ($W\ m^{-2}$)
$Q_{Internal}$	Internal heat gain within the building (human metabolism, lighting and appliance) ($W\ m^{-2}$)
Q_{Waste}	Waste heat released to outdoor by HVAC system ($W\ m^{-2}$)
R	Ratio of anthropogenic heat flux from building ($Q_{F,\ B}$) to energy consumption (Q_{EC})
ΔS_{o-uo}	Different in storage heat flux between occupied (o) and unoccupied (uo) building ($W\ m^{-2}$)
T_{ave}	Average indoor and outdoor air temperature (°C)
ΔT	Indoor and outdoor air temperature difference (°C)
U_W	Reference wind speed at height of upstream airflow ($m\ s^{-1}$)
V_{Stack}	Buoyance driven ventilation rate ($m^3\ s^{-1}$)
V_T	Total ventilation rate by combined wind and bouyance effect
V_W	Wind driven ventilation rate ($m^3\ s^{-1}$)

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