Local-Scale Urban Energy Balance Observation under Various Sky Conditions in a Humid Subtropical Region

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ABSTRACT

The present study presents local-scale urban energy balance observations under various sky conditions in a humid subtropical region. The study site is a typical urban residential area in Guangzhou in which building density is 38%, vegetation coverage is 36%, and mean building height is 21 m. The observation was conducted at a 110-m-high tower using the eddy covariance technique from September to November 2016. The median diurnal pattern and daily maxima were achieved for all radiation components and turbulent fluxes. The Bowen ratio (β) results indicated a predominant role for sensible heat flux (Q_H) in the daytime and latent heat flux (Q_E) at night. The sky conditions played a significant part in the urban surface energy exchanges, showing that the median daily maxima of net radiation (Q^*), Q_H , storage heat flux (ΔQ_S), surface albedo, and β all present a consistent order from large to small for clear, cloudy, and rainy days and a different order of rainy, clear, and cloudy days for Q_E . The mean daytime Q_H/Q^* , Q_E/Q^* , $\Delta Q_S/Q^*$, and β changed with urban density, while Q_E/Q^* and β also varied with vegetation fraction. Furthermore, the adaptability of net all-wave radiation parameterization (NARP), objective hysteresis model (OHM), and local-scale urban meteorological parameterization scheme (LUMPS) were validated, given the index of agreements of 0.998 and 0.951 for Q^* and ΔQ_S and the reasonable RMSEs for Q_H and Q_E . The present study helps to verify and improve the parameterizations of energy exchange over an urban surface in the humid subtropical region.

1. Introduction

In the humid subtropical region of China, urban climate dramatically changes with the fast urbanization of the region, and the changes have significant effects on urban heat island intensity, building energy consumption, and people's living environment. There are three horizontal scales in urban climate studies (Oke 2006): microscale, local-scale, and mesoscale, with spatial scales of $1\text{--}10^3$, $10^3\text{--}10^4$, and $10^4\text{--}10^5$ m, respectively. The local-scale urban neighborhoods with many human activities were our primary focus. Surface energy exchanges are the key to understanding the local-scale urban climate, and field observations of surface energy balance (SEB) are the most direct and objective way to study them.

Energy balance observations cannot only observe local energy flux changes with long periods but can also be used to verify the accuracy of a large number of energy balance models. Currently, the turbulent fluxes of sensible and latent heat have been widely observed using

the eddy covariance (EC) technique, the predominant method in the Flux Network (FLUXNET; Baldocchi et al. 2001), with a well-established theory (Campbell and Norman 1998; Lee et al. 2006). The measured terms include the components of net all-wave radiation and turbulent fluxes of sensible and latent heat, which are the major parts of the urban energy balance equation.

Virtually all observed and modeled estimates of the components of the energy balance of urban surfaces have been made since 1970 (Arnfield 2003). Recently, the majority of urban SEB observations were conducted in Europe and North America (e.g., Grimmond and Oke 2002; Nemitz et al. 2002; Christen and Vogt 2004; Velasco et al. 2011; Goldbach and Kuttler 2013; Chow et al. 2014; Kotthaus and Grimmond 2014a,b), while only a few were conducted in Asia (e.g., Moriwaki and Kanda 2004; Liu et al. 2012; Miao et al. 2012; Ao et al. 2016a; Ando and Ueyama 2017; Roth et al. 2017). Several studies focused on the (sub)tropical regions that are reviewed by Tejeda-Martínez and Jáuregui-Ostos (2005) as well as Roth (2007), for instance, the one by Velasco et al. (2011) and Roth et al. (2017). However,

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very limited studies have been conducted in the humid subtropical climate regions (Cfa, classified by Köppen climate classification), including those in Shanghai, China (Ao et al. 2016a), Tokyo, Japan (Moriwaki and Kanda 2004), and Sakai, Japan (Ando and Ueyama 2017). Furthermore, there is a dearth of robustly measured SEB data from dense urban core areas with local climate zone 1 (LCZ 1) (Stewart and Oke 2012), according to the review by Oke et al. (2017).

A large number of sophisticated urban energy balance models have been created and developed for understanding the process of surface energy exchanges, for example, the local-scale urban meteorological parameterization scheme (LUMPS) (Grimmond and Oke 2002), the improved mesoscale model (Martilli et al. 2002) and the SEB model (Pape and Löffler 2004), the surface urban energy and water balance scheme (SUEWS) (Järvi et al. 2011; Ward et al. 2016), and others. Grimmond et al. (2010, 2011) have reviewed and compared a large number of urban energy balance models. The urban energy balance model has clear physical significance and properties of portability and universality, which is a preferred method to analyze the local-scale urban climate. The results of energy balance observations help us to verify and improve parameterizations of energy exchange over complex urban surfaces (Christen and Vogt 2004).

LUMPS formulates in the framework of SEB of

$$Q^* = Q_H + Q_E + \Delta Q_S \quad (1)$$

where Q^* is net all-wave radiation, Q_H and Q_E are sensible and latent heat flux, and ΔQ_S is storage heat flux. It was proposed initially by Grimmond and Oke (2002) with some limitations on not including anthropogenic heat (Q_F) and requiring Q^* as an input parameter. The scheme was greatly improved afterward by Loridan et al. (2011), with the improvements on combining the net all-wave radiation parameterization (NARP) (Offerle et al. 2003) to calculate Q^* , and taking the influences of Q_F , vegetation phenology, and water availability into account. LUMPS is the focus of this study as it is one of the simplest urban SEB models and has a good performance with an input of only a few parameters from standard meteorological observations along with the necessary information on urban surface cover.

Guangzhou is a typical city in the humid subtropical region of China, with a hot-humid climate and diverse sky conditions. The objectives of the present study undertaken in Guangzhou are 1) to observe the temporal characteristics of local-scale urban energy balance exchanges under various sky conditions and 2) to validate

the adaptability of LUMPS in the humid subtropical region. This observation is novel in that it comes from the humid subtropical climate region from which more research is required, and also in that it provides the measured SEB data for the compact high-rise LCZ. Moreover, the validation of LUMPS with the observed radiation and turbulence fluxes is expected to enhance knowledge of urban SEB and provide an essential base for urban planning and resilience designs in humid subtropical regions.

2. Methods

a. Climate and site

The present study was conducted in Guangzhou, with the city center located at latitude 23°08'N and longitude 113°19'E. It is a typical megacity in the humid subtropical region of China (Fig. 1a). The long summers are hot and humid, with abundant rainfall, and winters are temperate and short. On average over 30 years (from 1981 to 2010), the monthly mean temperature is 26.9°C, the relative humidity (RH) is 75% for summer (from April to October), and those values are 17.9°C and 64%, respectively, for autumn (from November to December). Guangzhou is in the monsoon region, which experiences prevailing southeast winds in summer and north winds in winter. The annual sunshine time is approximately from 1500 to 2000 h. The yearly rainfall is around 1801 mm. All meteorological conditions are based on data provided by the National Meteorological Information Center (<http://data.cma.cn/>). Summer, with extremely hot and humid weather, is the most important season for the city. The total population exceeded 14 million, with a population density of 1883 people per square kilometer, at the end of 2016, based on data provided by the Statistical Bureau of Guangzhou (<http://www.gzstats.gov.cn/>).

According to the LCZ concept of Stewart and Oke (2012), we made a LCZ classification map of Guangzhou using the World Urban Database and Access Portal Tools (WUDAPT), as shown in Fig. 1b. The center of Guangzhou, which is an urban area with impervious roads, buildings, and scattered trees, was mainly classified into two LCZ types: a compact high-rise LCZ and a compact midrise LCZ (LCZ 1 and LCZ 2, respectively). When compared to an older classification for Guangzhou available from the WUDAPT website (<http://www.wudapt.org/>), our results show that, with rapid urbanization, the LCZ types for Guangzhou have shifted to the top levels with higher and more intensive buildings. We chose the west part of the Haizhu district in Guangzhou as the study site, that is, the area of 1-km radius around the tower as

FIG. 1. (a) Visible image map and (b) LCZ classification map of Guangzhou and (c) visible image map and (d) land classification map of the studied site. The visible image map was obtained by the *GeoEye-1* satellite on 22 Oct 2017. The land classification map is based on the GIS database, with a 1-km radius centered on the high tower (green star in the map) at the study site.

Fig. 1c shows, which contains the two LCZ types of central Guangzhou.

The study site is a typical local-scale urban residential area in which several main neighborhoods are made up of high-rise buildings that are compactly arranged; the site is considered LCZ 1. Moreover, the LCZ subclass is LCZ 8, so the study area could be defined as LCZ 1₈. According to the detailed GIS database (see Fig. 1d), the building density is 38%, the mean building height is 21 m, and the vegetation coverage is 36% for the whole study site. The building height separated into three types: low-rise (1–3 stories), midrise (3–9 stories), and high-rise buildings (above 9 stories), according to the classification of Stewart and Oke (2012). The green spaces are continuously distributed, with dense tree cover in the neighborhoods and sparse tree cover along the roads. The buildings' exterior surfaces are mainly light-color tiles, and a few are plaster. The roadways are covered by asphalt.

b. Data collection and processing

The energy exchange measurements were conducted at the top of a high tower. The high tower is located at

the center of the study site ($23^{\circ}04'44''\text{N}$, $113^{\circ}16'12''\text{E}$; see Fig. 1), is 25 m high and stands on the roof of a 28-story building with a width of 21 m (Fig. 2a). The choice of the tower meets the requirements of World Meteorological Organization (2008), which suggested that the measurements should be raised at least one building width above the top when the instruments are placed on top of a building. Moreover, the tower is a frame structure without an external wall, so the effect of the tower on the measurements could be ignored.

Three components of urban SEB were measured: net all-wave radiation, turbulent fluxes of sensible and latent heat. A net radiometer (NR01) (Table 1) was used to measure the net all-wave radiation Q^* , including incoming shortwave radiation ($K\downarrow$), reflected shortwave radiation ($K\uparrow$), incoming longwave radiation ($L\downarrow$), and outgoing longwave radiation ($L\uparrow$), at 1-min intervals. The turbulent sensible and latent heat fluxes were measured using the EC method; see Campbell and Norman (1998) for more details on the method. The EC system consisted of a sonic anemometer and an open path infrared gas analyzer, both of which were made by

FIG. 2. (a) The high tower, (b) recording system, and (c) instruments.

Campbell Scientific and sampled at 10 Hz, as shown in Table 1 and Figs. 2b and 2c.

All the instruments were mounted on a stand extending 2 m from the edge of the high tower in the south direction (the net radiometer was projected toward the right south direction, and the sonic anemometer and open path infrared gas analyzer were oriented southeast–northwest, see Figs. 2b,c) and were connected to a datalogger (CR3000, Campbell Scientific). The measurement point height was 110 m above the ground level, which equates to a ratio of 5.2 of the mean building height Z_h of the study site and falls in the inertial sublayer.

The observations were conducted continuously in three months from 11 September to 28 November 2016.

The method by Zhang (1934) that is nationally acknowledged and adopted by the Chinese standard QX/T 152–2012 was used for season classification. It takes the local pentad-average air temperature as criterion, a period of that temperature larger than 22°C as summer and that temperature from 10° to 22°C as spring or autumn. The average air temperatures are 26.8° and 25.2°C for September and October, respectively, and it was higher than 22°C even on many days in November. Accordingly, the study period is identified as two months of summer and one month of autumn, which are the representative seasons for the humid subtropical climate regions. It is worth mentioning that the study year 2016 was wetter when comparing with the average climate pattern in over 30 years.

TABLE 1. Instrumentations for radiation and turbulent fluxes.

Measured content	Instrument	Model	Manufacturer	Precision and (measurement range)	Sample
Net radiation	Net radiometer	NR01	Hukseflux	For daily sums: $\pm 10\%$ ($0\text{--}2000\text{ W m}^{-2}$)	1 min
Sensible and latent heat flux	Sonic anemometer	CSAT3A	Campbell	U_x : 1 mm s^{-1} ($\pm 30\text{ m s}^{-1}$) U_y : 1 mm s^{-1} ($\pm 60\text{ m s}^{-1}$) U_z : 0.5 mm s^{-1} ($\pm 8\text{ m s}^{-1}$) Wind direction: 0.6° ($\pm 170^\circ$) Sonic temperature: 0.025°C (-50° to $+60^\circ\text{C}$)	10 Hz
	Gas analyzer	EC150	Campbell	H_2O : $0.006\text{ mmol mol}^{-1}$ ($0\text{--}72\text{ mmol mol}^{-1}$)	10 Hz
	Ambient temperature	100K6A11A	BetaTherm	$\pm 0.15^\circ\text{C}$ (-30° to $+50^\circ\text{C}$)	10 Hz

The data analysis was performed based on 30-min block averages and using Beijing time that is 8 h later than coordinated universal time (UTC). We discarded the data during rainfall and the subsequent 30-min period, according to [Kotthaus and Grimmond \(2012, 2014a\)](#). Before calculating half-hourly covariance, some necessary data corrections were applied, including spiking of raw data ([Vickers and Mahrt 1997](#)), double rotation ([Kaimal and Finnigan 1994](#)), sonic temperature ([Schotanus et al. 1983](#)), and theoretical high-frequency spectral ([Massman 2000](#)) and crosswind ([Liu et al. 2001](#)) corrections; the water vapor was also corrected for density fluctuations ([Webb et al. 1980](#)). Data quality was estimated using two tests: the steady-state test and the developed turbulent conditions test ([Foken et al. 2004](#)), and the data that did not pass these tests were eliminated.

The meteorological conditions observed at the National Weather Station (NWS) of Guangzhou (23°07'48"N, 113°17'24"E, the height is 72 m above sea level, and approximately 6 km from the study site; see [Fig. 1a](#)) in 2016 were obtained. The NWS was surrounded by the compact midrise and high-rise buildings, which is similar to the surroundings of the study site. These are considered representative of the atmospheric conditions in the central area of Guangzhou and could be used as the reference of the study site. The parameters included air temperature, relative humidity, shortwave radiation, precipitation, wind speed, and wind direction.

c. Data classification and availability

We used a bulk daily shortwave transmission (τ_{day}) to classify the sky conditions as clear, rainy, and cloudy:

$$\tau_{\text{day}} = K_{\downarrow, \text{day}} / G_0 \quad (2)$$

where $K_{\downarrow, \text{day}}$ is the daily total downward shortwave radiation at the measurement height; G_0 is daily total solar radiation at the top of the atmosphere, calculated referring to [Ao et al. \(2016b\)](#).

According to [Dou et al. \(2019\)](#), [Kawai and Kanda \(2010\)](#), and [Duffie and Beckman \(2013\)](#), if τ_{day} was larger than 0.50, the day was classified as a clear day. If any rainfall was recorded at the meteorological station, the day was classified as a rainy day. The remaining days were classified as cloudy days.

The availability of data for different sky conditions is shown in [Table 2](#). The availability of radiation data is 89% for all the study days, and data loss is mainly caused by insufficient power supply for the instruments. The availability of turbulence data is 61%, where 30% of data are missing because of the low voltage of instruments, and 9% of data are missing because of the rain's impact.

TABLE 2. Data availability for different sky conditions by the days.

Class	Days for radiation data (for turbulence data)			
	Sep	Oct	Nov	Total
All days	20(21)	31(12)	28(28)	79(61)
Clear days	11(9)	6(0)	1(1)	18(10)
Rainy days	3(8)	14(6)	10(10)	27(24)
Cloudy days	6(4)	11(6)	17(17)	34(27)

d. Source area calculations

The radiation source area is for the radiometer, and the turbulence source area is for the thermometer, hygrometer, gas analyzer, and sonic anemometer ([Oke 2006](#)). The two kinds of source areas usually differ: the radiation source area is, in general, a circular patch with the radiometer at the center, whereas the turbulence source area is an ellipse in a planar view, with the instruments always outside the area.

1) RADIATION SOURCE AREA

For the Lambertian surfaces, the radiation source area is mainly a function of radiometer height. [Schmid et al. \(1991\)](#) provided an equation to acquire the radius (r) of the radiation source area:

$$r = Z_1 \left(\frac{1}{F} - 1 \right)^{-0.5}, \quad (3)$$

where F is the view factor, and Z_1 is the height of the radiometer.

2) TURBULENCE SOURCE AREA

After [Schmid and Oke \(1990\)](#) proposed the definition of turbulence source area (also called footprint), many models have been proposed: the scalar Flux Source Area Model (FSAM) by [Schmid \(1994, 1997\)](#), the footprint model by [Kormann and Meixner \(2001\)](#), and the footprint flux prediction (FFP) model by [Kljun et al. \(2015\)](#). In the present study, the FFP model was adopted to estimate the turbulence source area as the model was developed to analyze the long-term series.

In the FFP model, the required input parameters include $Z_m = Z - Z_d$ (Z is the sensor measurement height, and Z_d is the zero-plane displacement height), roughness length Z_0 , boundary layer height h , Obukhov length L , friction velocity u_* , wind speed and direction, and the standard deviation of lateral velocity fluctuations σ_v . The turbulence source area will be larger with a higher Z_m , a lower Z_0 , a larger mean wind speed, a higher h , a smaller σ_v , or a smaller u_* according to [Kljun et al. \(2015\)](#).

Most of the needed parameters were derived directly from the measured data, except for Z_m , Z_0 , and h .

FIG. 3. Daily meteorological conditions during the study period. The parameters are mean values except for the precipitation and shortwave radiation, which are the cumulative values.

Among these, Z_0 and Z_d were estimated using the GIS database together with morphometric methods. There are some morphometric methods based on mean building height Z_h , plan area fraction λ_p , and frontal area index λ_f such as those in Macdonald et al. (1998), Raupach (1994), and Bottema (1995, 1997). Grimmond and Oke (1999a) reviewed them and suggested a rank order for these methods. The method of Macdonald et al. (1998) was adopted in the present study because it is applicable across the full range of building densities. The input parameters of Z_h , λ_p , and λ_f were acquired based on the *GeoEye-1* stereo satellite imagery with a 0.41-m resolution, as shown in Fig. 1d. The h was calculated for the neutral to stable and convective conditions separately, in which the interpolation formula of Nieuwstadt (1981) was used for the former and the slab model of Batchvarova and Gryning (1991) based on a simplified turbulence kinetic energy (TKE) equation was used for the latter.

3. Results and discussion

a. Meteorological conditions

The daily meteorological conditions at the NWS are shown in Fig. 3, and the monthly mean values are

presented in Table 3. The air temperature and shortwave radiation declined month by month and within the most comfortable range for human outdoor activities.

The monthly mean relative humidities were all approximately 80%. The cumulative precipitation decreased significantly month by month. It can be further observed in Fig. 3 that the daily mean vapor pressure deficit (VPD) was positively related to air temperature and negatively related to precipitation.

The wind frequency distribution at the NWS and the study site are shown in Fig. 4. Both sites are within the height of the inertial sublayer and have the same surroundings, so the NWS could be treated as the reference of the study site. The wind speeds ranged from 0 to 6.9 m s^{-1} and averaged 2.4 m s^{-1} at the NWS during the study period. The main wind direction observed at the NWS during the study period (Fig. 4a) was quite similar to that in the hottest period from June to August (see Fig. 4b); both have the most prevailing wind direction of north. The wind conditions measured at the study site showed slight differences with those of the NWS: the main wind direction was northwest (Fig. 4c), the time-average wind speed was 2.5 m s^{-1} , the wind directions in the 270° – 360° sector accounted for 45% of the total

TABLE 3. Monthly meteorological conditions during the study period. The parameters are mean values except for the precipitation, which is the cumulative value.

	Air temperature ($^\circ\text{C}$)	Pressure (hPa)	VPD (hPa)	Daily total shortwave radiation ($\text{MJ m}^{-2} \text{ day}^{-1}$)	Precipitation (mm month^{-1})	Wind speed (m s^{-1})
Sep	26.8	999.30	6.99	15.07	210.5	2.06
Oct	25.2	1003.30	6.95	13.54	140.0	2.64
Nov	19.1	1009.82	4.45	10.28	61.8	2.50
Sep to Nov	23.7	1004.14	6.13	12.96	412.3	2.40

FIG. 4. Wind frequency distribution at (a) the NWS from September to November, (b) NWS from June to August, and (c) the study site from September to November.

sample data, and the low wind speeds ranging from 0 to 4 m s^{-1} accounted for 89%. The wind directions during the measured period were not representative as the prevailing wind direction is southeast over the years.

Many researchers have suggested that atmospheric stability is a major factor for turbulence source area (Kljun et al. 2002; Kormann and Meixner 2001). Atmospheric stability is defined as $\zeta = (Z - Z_d)/L$ and can be divided into three categories: unstable ($\zeta < -0.1$), near-neutral ($-0.1 \leq \zeta < 0.1$), and stable ($\zeta \geq 0.1$) conditions (Kotthaus and Grimmond 2014a). The atmospheric stability of the present study is shown in Fig. 5. The unstable condition was dominant during the daytime, and the proportion of the stable and near-neutral conditions at nighttime were much larger than the daytime. The stable condition fraction was relatively small.

b. Modeled source areas

1) RADIATION SOURCE AREA

The modeled radiation source area is shown by the red dashed line in Figs. 1c and 1d. The radius r of the radiation source area is 330m with the 90% view factor. Within the radiation source area, the building density is

34%, and the greening coverage is 33%, both of which are very close to those of the whole study area. As a result, it is confirmed that the measured radiation flux can competently represent the study site situation.

2) TURBULENCE SOURCE AREA

By using the GIS database of the study site, a series of heights needed for modeling turbulence source area were obtained, as shown in Table 4; λ_p is equal to the building density of 0.38. As the front buildings would block winds to the rear ones in terms of the main wind direction, we merged the nearby buildings into one to acquire a more accurate frontal area. The frontal area in the main wind direction of 315° was determined to be 1.6 km^2 , and λ_f was determined to be 0.52. These results were substituted into the morphometric method of Macdonald et al. (1998), and Z_0 and Z_d were obtained accordingly.

Knowing the above input parameters, we used the FFP model compiled in MATLAB to model the turbulence source area of the study site, as shown in Fig. 6. It is evident that the source area of the stable and near-neutral condition was more extensive than that of the unstable condition. The areas contributing to 50% of the

FIG. 5. Atmospheric stability ζ during the study period, shown as (a) a frequency histogram and as (b) a frequency distribution categorized by time of day and the three stability conditions.

TABLE 4. Source area characteristics at the study site.

	Source area characteristic	Value
Height (m)	Mean building height Z_h	21
	Roughness length Z_0	2.3
	Displacement height Z_d	13.5
	Sensor height Z	110
	Height of building hosting tower	85
	Tower height above the roof	25

source area were approximately 1000 m and exceeded 1000 m in the main northeast wind direction under the two atmospheric conditions. These results are larger than those of [Kotthaus and Grimmond \(2014b\)](#) and [Liu et al. \(2012\)](#), as the measurement height is much higher in the present study.

c. Radiation components

Radiative flux energy is the most critical sector of the urban SEB. All four components of the radiation budget during the study period are shown in [Fig. 7](#). For a better understanding of the difference with sky conditions, we separated the results into three sky conditions as shown in [Fig. 8](#).

1) SHORTWAVE RADIATIONS

At the study site, the daily maxima of $K\downarrow$ appeared around noon and ranged from nearly 200 to 1000 W m^{-2} during the study period, and the time period, latitude, and sky conditions played crucial roles in that broad range. In the same time period, the range is smaller in London ([Kotthaus and Grimmond 2014a,b](#)), where more cloudy days occurred and the daily maxima $K\downarrow$

changed from 200 to 800 W m^{-2} , and also in Shanghai ([Ao et al. 2016b](#)) and Tokyo ([Moriwaki and Kanda 2004](#)), where more clear days occurred and the daily maxima $K\downarrow$ changed from nearly 500 to 870 W m^{-2} . It is obvious that the closer to the equator, the larger of the magnitude of $K\downarrow$.

The daily maxima of $K\uparrow$ appeared around noon and ranged from approximately 20 to 120 W m^{-2} during the study period. $K\downarrow$ and $K\uparrow$ presented a similar tendency, and significantly decreased month by month for the clear days while changing slightly with months for the rainy and cloudy days. The lowest values of both $K\downarrow$ and $K\uparrow$ occurred in the rainy days.

2) LONGWAVE RADIATIONS

At the study site, the daily maxima of both $L\downarrow$ and $L\uparrow$ appeared after noon, showing a noticeable time lag with that of solar radiation; $L\downarrow$ ranged from 280 to 460 W m^{-2} , and $L\uparrow$ ranged from 360 to 530 W m^{-2} . This confirmed that [Oke \(1987\)](#) indicated that the value of $L\uparrow$ is greater than $L\downarrow$, because the values of surface temperature and emissivity are greater than their atmospheric counterparts. Besides, the value of $L\uparrow$ was more variable than $L\downarrow$ as [Fig. 7](#) shows, probably because the urban surface temperature varied considerably in a day; $L\downarrow$ increased with cloud cover, as the magnitude of $L\downarrow$ on the rainy days was larger than that on the clear and cloudy days. This agrees with [Flerchinger et al. \(2009\)](#), who suggested the variation in $L\downarrow$ is a function of near-surface atmospheric conditions (temperature and humidity) and the presence of mid- or low-level clouds. By comparing [Fig. 7](#) with [Fig. 3](#), it can be seen that the time series of $L\uparrow$ was close to that of

FIG. 6. The turbulence source area of the visible image map for (a) unstable and (b) stable and near-neutral atmospheric stability conditions.

FIG. 7. Observed 10-min average (gray dots) fluxes from the high tower for incoming shortwave radiation ($K\downarrow$), reflected shortwave radiation ($K\uparrow$), incoming longwave radiation ($L\downarrow$), outgoing longwave radiation ($L\uparrow$), net all-wave radiation (Q^*), and its daily means (black diamonds) and daily totals (white triangles). Shortwave radiation is for sunlight hours from 0600 to 1800, and longwave and net all-wave radiations are for a whole day.

near-surface air temperature, suggesting that the air temperature is affected by the thermal properties of the land surface. This consistency was evident on the clear and cloudy days, but not on the rainy days, as Fig. 8 shows.

The net all-wave radiation Q^* combines all four radiative components and is related to the sun's elevation, surface characteristics, cloud cover, and so forth. At the study site, the daily maxima of Q^* ranged from 200 to 800 W m^{-2} , and the median diurnal pattern of Q^* was

similar to that of $K\downarrow$ under various sky conditions, except for being negative at nighttime.

3) SURFACE ALBEDO

Surface albedo, as a critical parameter for weather forecasting and climate modeling, determines the energy partition between the surface and atmosphere and influences land surface temperature, evapotranspiration, energy balance, etc. (Liu et al. 2008). The surface albedo was calculated as the ratio of the reflected to

FIG. 8. Median diurnal variation (solid lines) of radiation components under clear, rainy, and cloudy days with interquartile range (IQR, shaded)

incoming solar radiation flux ($\alpha = K\uparrow/K\downarrow$) under the conditions that both were larger than 2 W m^{-2} . The diurnal variation in surface albedo showed a general U-shape pattern, as seen in Fig. 9, with larger values in both early morning and late afternoon and lower values during the rest of the daytime.

The surface albedo values were nearly 0.12 during most times of the day, which corresponds to the large field of view including complicated morphometric configurations and the dark-colored surfaces of road and roofs at the study site. This is close to that of Basel, Switzerland (Christen and Vogt 2004), but far from that of Los Angeles, California, and Chicago, Illinois

(Offerle et al. 2003), most likely because of the morphometric configuration and surface materials. During the periods of early morning and late afternoon, the surface albedo was largest on the clear days, followed by that on the cloudy days, and the albedo on the rainy days was smallest on November, as Fig. 9 shows. This probably was due to the reflection of direct solar radiation caused the large surface albedo, and the direct solar radiation was active on the clear days and weak on the cloudy and rainy days (Lucht et al. 2000).

The variations in median surface albedo with solar elevation and solar azimuth angle and the sun-path diagram of Guangzhou are shown in Fig. 10. The surface

FIG. 9. Median diurnal variation of surface albedo under various sky conditions for three months.

FIG. 10. Median surface albedo as functions of solar elevation angle when (a) the sun is in the east (E), (b) when the sun is in the west (W), and as functions of (c) solar azimuth angle and (d) together with the sun-path diagram of Guangzhou (the shaded area for the study period from September to November).

albedo decreased gradually with the increasing solar elevation, and the gradient was more evident on the clear days (Figs. 10a,b). This corresponds well to the findings of Aida (1982), Kotthaus and Grimmond (2014a,b), and Ao et al. (2016b). The higher surface albedo that occurred at a lower solar elevation was mainly caused by more reflected solar radiation at a smaller angle of incidence. The results also show a greater decreasing slope when the sun was in the west, indicating that the variation in surface albedo was more evident during sunset than at sunrise. This is opposite to the results obtained in London (Kotthaus and Grimmond 2014a,b) and Shanghai (Ao et al. 2016a,b). This can be explained by the heterogeneity around the site. The west direction of study sites in London and Shanghai were covered by a larger fraction of vegetation, while there are more high buildings in the present study. Figure 10c shows an increase from 0.12 to 0.50 when the solar azimuth angle changed from 140° to 80° in the early morning or from 240° to 280° in the late afternoon, suggesting that the surface albedo apparently varied with solar azimuth.

d. Surface energy exchanges

The median diurnal patterns of the absolute magnitude of Q^* , Q_H , Q_E , ΔQ_S , and Bowen ratio β are

presented for all days and various sky conditions in Fig. 11. ΔQ_S was calculated as the residual term of the SEB, in which Q_F was estimated and added to Q^* [see section 3d(2)]. All the results exhibited a diurnal pattern that is high in the daytime and low in the nighttime.

1) SENSIBLE AND LATENT HEAT FLUXES

Sensible heat flux always is a main contributor to energy transport away from the surface into the urban boundary layer (Kotthaus and Grimmond 2014a). From Fig. 11, Q_H was the largest at 1230, 1300, 1330, and 1400, with median daily maxima of 118, 171, 72, and 113 W m^{-2} for the overall, clear, rainy, and cloudy days, respectively. The daytime Q_H was largest on the clear days, followed by that on the cloudy days, and the daytime Q_H on the rainy days was least, following the same order of the net all-wave radiation. At night, Q_H was close to zero on the clear days and rainy days but higher than zero during most of the time on the cloudy days. This result is similar to that observed in London (Kotthaus and Grimmond 2014a) and Basel (Christen and Vogt 2004), where a majority of Q_H remained positive during nighttime.

Q_E exhibited a smaller diurnal variation than that of Q_H , with median daily maxima of 66, 106, 134, and

FIG. 11. Median diurnal pattern of net all-wave radiation (Q^*), sensible heat flux (Q_H), latent heat flux (Q_E), storage heat flux (ΔQ_S), and Bowen ratio (β) for (a) all days and various sky conditions of (b) clear, (c) rainy, and (d) cloudy days.

52 W m^{-2} for the overall, clear, rainy, and cloudy days, respectively, as shown in Fig. 11. The daytime Q_E on clear and rainy days was higher than that of the cloudy days; likewise, the nighttime Q_E was highest on rainy days, suggesting that strong radiation and high air temperature can promote evaporation, and abundant rainfall can provide more wet surfaces for long-time evaporation.

The daily maxima of median β occurred in the daytime, with magnitudes of 2.1, 2.6, 1.1, and 2.5 for overall, clear, rainy, and cloudy days, respectively, as shown in Fig. 11. The median values of β were larger than one during most of the daytime, indicating that Q_H dominated the surface energy exchanges in the daytime, but were lower than one at night, indicating more pronounced evapotranspiration effects and dominant role of Q_E at night. The median values of nighttime β were higher than zero in most cases. This was mainly caused by the variations of Q_H as the nighttime Q_E was always positive for all conditions.

2) ANTHROPOGENIC AND STORAGE HEAT FLUXES

Q_F is substantial and not negligible in the high-rise building residential areas. The large-scale urban consumption of energy (LUCY) model (Allen et al. 2011) was adopted in the present study both for the field observation and LUMPS validation. A fraction of vehicles

on the road was assumed as 0.8 and the average speed was 48 km h^{-1} . The International Road Federation (IRF) World Road Statistics 2005, Gridded Population of the World (GPW), version 3 (v3), dataset (2005), and energy consumption from a dataset in 2011 were used. Accordingly, the calculation by the LUCY model showed a minimum of 2.0 W m^{-2} at night and a maximum of 11.6 W m^{-2} in the daytime. The mean value of Q_F in the study site during the whole study period was estimated as 7.0 W m^{-2} .

The median daily maxima of ΔQ_S were 287, 453, 161, and 306 W m^{-2} for the overall, clear, rainy, and cloudy days, respectively, as shown in Fig. 11. The average daytime partitioning of Q^* dissipated by ΔQ_S was approximately 54%, which is definitely larger than that of Q_H and Q_E [see details in section 3d(3)], suggesting that the heat gain Q^* was mostly dedicated to ΔQ_S both during daytime and nighttime.

3) COMPARISONS WITH OTHER URBAN SITES

The mean ratios of energy partitioning (Q_H/Q^* , Q_E/Q^* , $\Delta Q_S/Q^*$) normalized by Q^* at the study site are shown in Fig. 12. In the daytime, the majority of energy is partitioned into ΔQ_S , followed by Q_H , and only with a small proportion for Q_E .

FIG. 12. Flux ratios of energy partitioning (Q_H/Q^* , Q_E/Q^* , $\Delta Q_S/Q^*$) normalized by Q^* .

For better understanding the differences between various urban sites in different climates and the physical meanings of the normalized energy partitioning, we collected a series of SEB observations in the (sub) urban sites in Table 5 in both the (sub)tropical and temperate climate regions. These mean daytime ratios of Q_H/Q^* , Q_E/Q^* , $\Delta Q_S/Q^*$, and β are useful to compare other studies with different seasons and different magnitude of Q^* forcing. The changes of mean daytime Q_H/Q^* , Q_E/Q^* , $\Delta Q_S/Q^*$, and β with vegetation fraction and urban density [expressed as $Z_{hl} \lambda_p$ (i.e., the product of mean building height and plan area fraction of building)] (Oke et al. 2017) are shown in Fig. 13 for the sites.

In the present study, the average daytime partitioning of Q^* (for $Q^* > 0 \text{ W m}^{-2}$) into Q_H was approximately 33%, which is much smaller than that of the other sites in Table 5. From Fig. 13a it can be seen that the higher the urban density, the lower the ratio of Q_H/Q^* is. It is true for the daytime, mainly because more heat was stored in the buildings, as the storage heat flux in Fig. 13d shows. The coefficient of determination R^2 is only 0.28, indicating that other factors, such as the thermal properties of roof, wall, and road, may play a role in the values of Q_H as well.

The average daytime partitioning of Q^* into Q_E was approximately 21%, which is smaller than that of Q_H/Q^* and $\Delta Q_S/Q^*$ in this study. However, this is still larger than that of sites in hot desert climate regions, such as Me98, Me03, and Me06, indicating that Q_E accounted for a significant effect on the urban SEB in the humid subtropical regions. From Figs. 13b and 13e it can be seen that the Q_E/Q^* ratio is a function of both urban density and vegetation fraction. The Q_E/Q^* increases with the decreasing urban density ($R^2 = 0.48$) and increasing vegetation fraction ($R^2 = 0.36$).

The mean daytime β (2.16) at the study site is similar with that of Ba02u1, Ba02u2, Ob10u, Tk01, Sh13, Ph12, Si06–13, and Tu90, with the values ranged from 1.77 to 2.62, and lower than that of Me93, Me98, and Me06, with the values of 7.4, 4.4, and 2.9, respectively. Figures 13c and 13f further indicate that β increases with increasing urban density ($R^2 = 0.34$) and decreasing vegetation fraction ($R^2 = 0.42$).

The mean daytime $\Delta Q_S/Q^*$ of this study reports a lower value than that of Me93 and Sh13. This is mainly related to urban density, as $\Delta Q_S/Q^*$ increases significantly with urban density ($R^2 = 0.73$).

From all ratios in Fig. 13, it can be found that all compared ratios vary a lot for the sites in the sub(tropical) regions, while they stay in the middle range and vary slightly for the sites in temperate regions. This is probably caused by the limited samples of the temperate regions, but it is definitely worthwhile to further analyze the SEB data in the sub(tropical) regions.

e. LUMPS validation

The performance of LUMPS were evaluated in this study by using the Linear regression method (intercept a , slope b , and coefficient of determination R^2), mean bias error (MBE), and root-mean-square error (RMSE) as follows:

$$\text{MBE} = \frac{1}{n} \sum_{i=1}^n (P_i - O_i), \quad \text{and} \quad (4)$$

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2}, \quad (5)$$

where P_i are model-predicted values and O_i are observed values. According to Willmott (1982), the statistical parameters of systematic RMSE (RMSE_S), unsystematic RMSE (RMSE_U), and the index of agreement (d) were adopted as well:

$$\text{RMSE}_S = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i^* - O_i)^2}, \quad (6)$$

$$\text{RMSE}_U = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i^* - P_i)^2}, \quad \text{and} \quad (7)$$

$$d = 1 - \frac{\sum_{i=1}^n (P_i - O_i)^2}{\sum_{i=1}^n (|P_i| + |O_i|)^2}, \quad (0 \leq d \leq 1), \quad (8)$$

where $P_i^* = a + bO_i$, a and b are the least squares regression coefficients of P_i and O_i , $P_i' = P_i - \bar{O}$, $O_i' = O_i - \bar{O}$, and

TABLE 5. Surface characteristics of the compared energy balance sites.

Site	Lat, lon	Köppen	Compared period	λ_p	λ_v	Z_h	Urban density = $Z_h \times \lambda_p$	Reference
Guangzhou (Gz16)	23°08'N, 113°19'E	Cfa	Sep–Nov 2016	38%	36%	21.0	7.980	This study
Tokyo, Japan (Tk01)	35°34'N, 139°41'E	Cfa	Jul 2001	32.6%	20.6%	7.3	2.380	Moriwaki and Kanda (2004)
Shanghai, China (Sh13)	31°11'N, 121°26'E	Cfa	Sep–Nov 2013	23%	14%	35.9	8.257	Ao et al. (2016a)
Basel U1 (Ba02u1)	47°34'N, 07°36'E	Cfb	10 Jun–10 Jul 2002	54%	16%	14.6	7.884	Christen and Vogt (2004)
Basel U2 (Ba02u2)	47°33'N, 07°35'E	Cfb	10 Jun to 10 Jul 2002	37%	31%	12.5	4.625	Christen and Vogt (2004)
Oberhausen, Germany (Ob10u)	51°29'N, 6°52'E	Cfb	Oct 2010	46.8%	18%	14.0	6.552	Goldbach and Kuttler (2013)
Mexico City (Me93)	19°26'N, 99°8'W	Cwb	Dec 1993	54%	1%	18.4	9.936	Oke et al. (1999)
Mexico City (Me98)	19°26'N, 99°8'W	Cwb	Dec 1998	n.a.	<2%	n.a.	n.a.	Tejeda-Martínez and Jáuregui-Ostos (2005)
Mexico City (Me06)	19°26'N, 99°8'W	Cwb	Mar 2006	57%	6%	12.0	6.840	Velasco et al. (2011)
Phoenix (Ph12)	33°29'N, 112°9'W	BWh	Oct 2012	26.4%	14.6%	4.50	1.189	Chow et al. (2014)
Singapore (Si06–13)	1°19'N, 103°55'E	Af	14 Mar–8 Jun; 27 Sep–30 Nov 2006–13	39%	15%	9.30	3.627	Roth et al. (2017)
Tuscon (Tu90)	32°7'N, 110°56'W	BWh	10–23 Jun 1990	23%	28%	5.20	1.196	Grimmond and Oke (2002); Roth (2007)

$\bar{O}$ is the mean value of the observed. The value of RMSE should be minimized so that the model is predicting at peak accuracy. Concerning a “good” model, the magnitude of RMSEs should approach zero, whereas the value of $RMSE_U$ should approach RMSE (Stunder and Sethuraman 1986). A value of d close to 1.0 indicates that the model prediction approaches the observed variable.

1) NET ALL-WAVE RADIATION

Q^* can be obtained easily from parameterization using measured or modeled solar radiation (Newton et al. 2007). We derived it from the NARP (Offerle et al. 2003) as Loridan et al. (2011) does. The observed $L \downarrow$ was used in NARP model since it has the best performance to calculate Q^* based on the evaluation of Loridan et al. (2011). The surface albedo α and emissivity ε were set as 0.08 and 0.98 for vegetation, 0.12 and 0.91 for paved road, and 0.15 and 0.95 for buildings, respectively.

Comparison of the observed and modeled Q^* are plotted in Figs. 14a and 14e and the statistics are shown in Table 6. The use of NARP to model Q^* yields a good performance with a high R^2 and relatively low MBE and RMSE. This corresponds well to the fact that all the scatter points are close to the line $y = x$ in Fig. 14a, and two lines in Fig. 14e were overlapped.

2) STORAGE HEAT FLUX

The storage heat flux (ΔQ_S) is very difficult to measure directly (Grimmond and Oke 1999b), requiring extensive observations that cover the diversity of buildings, canyons, and other elements of the urban canopy volume. Hence, it is usually measured as the residual term (Q_{RES}) of the SEB or predicted by using the objective hysteresis model (OHM) (Grimmond et al. 1991; Grimmond and Oke 1999b) as LUMPS does. The OHM equation is

$$\Delta Q_S = \sum_{i=1}^n (f_i a_{1i}) Q^* + \sum_{i=1}^n (f_i a_{2i}) \left(\frac{\partial Q^*}{\partial t} \right) + \sum_{i=1}^n (f_i a_{3i}), \quad (9)$$

where f_i is the fraction of each of the i surface types, a_1 is the coefficient of the direct relation between ΔQ_S and Q^* , a_2 is the coefficient accounts for hysteresis between ΔQ_S and Q^* , and a_3 is an intercept term.

In the present study, we classified the land surfaces into three types following LUMPS and obtained the fractions for vegetation, impervious surfaces, and rooftops as 36%, 26%, and 38%, respectively, according to the GIS database of the study site. The OHM coefficient of average vegetation was used for vegetation, that of Doll et al. (1985) was used for impervious surfaces, and that of concrete was provided by Asaeda and Ca (1993) for rooftops.

seen that Q_H is overestimated except for the maxima in daytime, and Q_E is underestimated both day and night. This agrees with the study of [Loridan et al. \(2011\)](#) showing that LUMPS would benefit from a more accurate partitioning of the available energy between the two turbulent processes. The statistics of R^2 and d values for nighttime are lower than those of daytime both for Q_H and Q_E , indicating that the performance is better for daytime. The RMSE_S of Q_E is larger than its RMSE_U for all cases, indicating a large error in the modeled Q_E by LUMPS.

The present results were compared with the evaluation of LUMPS at cities of Łódź, Poland (Loridan et al. 2011), and Shanghai (Ao et al. 2017). The RMSE of Q_H ranges from 30 to 39 W m^{-2} for Łódź, and from 47.2 to 115.7 W m^{-2} for Shanghai. The value of this study (36.5 W m^{-2}) is close to that of Łódź. In terms of RMSE of Q_E , the result of this study (42.8 W m^{-2}) is slightly larger than that of Łódź (from 21.6 to 32.9 W m^{-2}) and within the range of Shanghai (from 17.1 to 53.1 W m^{-2}). Models of anthropogenic energy usage, irrespective of water balance, the net advection of heat and moisture into/out of the area, and some other sinks (sources), are among the possible reasons for such a bias of LUMPS.

4. Conclusions

In the present study, local-scale urban energy balance observations were conducted in Guangzhou from September to November of 2016, and the adaptability of

$$Q_E = \frac{\alpha}{1 + (\gamma/s)}(Q^* - \Delta Q_S) + \beta, \quad (11)$$

where s is the slope of the saturation vapor pressure versus temperature curve in $\text{Pa } ^\circ\text{C}^{-1}$, γ is the psychrometric constant, and α and β are empirical parameters. The empirical parameters were obtained using the regression method by [Grimmond and Oke \(2002\)](#).

The performances of the modeled Q_H and Q_E when using LUMPS were tested by comparison with the field observations, as shown in Table 6 and Figs. 14c,d,g,h. The overall RMSE are 36.5 W m^{-2} for Q_H and 42.8 W m^{-2} for Q_E . From Figs. 14g and 14h, it can be

FIG. 14. Observed vs modeled (a) Q^* , (b) ΔQ_s , (c) Q_H , and (d) Q_E . The linear regression with solid lines is shown. Diurnal mean observed and modeled (e) Q^* , (f) ΔQ_s , (g) Q_H , and (h) Q_E . MBE, RMSE, and d statistics are given.

LUMPS in the humid subtropical region was validated using the field observations. The following conclusions were obtained.

The study site is a typical local-scale urban residential area in a humid subtropical region and contains two representative LCZ types of central Guangzhou, with a building density of 38%, vegetation coverage of 36%, mean building height of 21 m, roughness length of 2.3 m, and zero-plane displacement of 13.5 m. The observations were conducted at the center of the site at a height of 110 m, with a radius of 330 m for the 90% view factor of the radiation source area, and distances of nearly 1000 m and over 1000 m for the 50% turbulent source area with the main wind direction of northwest under various atmospheric conditions.

For the whole study period, the median solar radiation values were positive in daytime and zero at night, with the daily maxima of $K\downarrow$ ($K\uparrow$) from 200 (20) to 1000 (120) W m^{-2} occurring at noon. The median longwave

radiations always remained positive, with the daily maxima of $L\downarrow$ ($L\uparrow$) from 280 (360) to 460 (530) W m^{-2} occurring after noon. The median diurnal pattern of Q^* was similar to that of $K\downarrow$ except for being negative at nighttime, with daily maxima from 200 to 800 W m^{-2} . The diurnal pattern of surface albedo showed a general U shape, with most of the daytime being nearly 0.12 and higher values in the early morning and late afternoon, suggesting an increasing surface albedo with a smaller solar elevation.

For the whole study period, the median Q_H was not less than zero even during nighttime, and its daily maximum was 118 W m^{-2} . The median Q_E exhibited a diurnal variation gentler than that of Q_H , with a median daily maximum of 66 W m^{-2} . The median β was larger than one during most of the daytime and lower than one at night, suggesting a dominant role of Q_H in the daytime and of Q_E at night. The median diurnal pattern of ΔQ_s was similar to that of Q^* , with daily maxima of 287 W m^{-2} .

TABLE 6. Statistical results for measured vs modeled Q^* , ΔQ_s , Q_H , and Q_E .

Variable	Conditions	Number	Slope	Intercept	R^2	MBE	RMSE	RMSE _s	RMSE _U	d
Q^*	Overall	2315	0.94	4.33	0.997	-0.3	15.2	11.0	10.6	0.998
	Daytime	1169	0.93	7.54	0.994	-6.1	20.5	15.5	14.4	0.997
	Nighttime	1146	0.96	3.84	0.988	5.7	6.4	5.9	2.6	0.983
ΔQ_s	Overall	2315	0.80	-0.24	0.839	-3.7	59.6	30.2	51.3	0.951
	Daytime	1169	0.74	19.83	0.771	-8.9	78.0	42.6	64.8	0.928
	Nighttime	1146	0.25	-52.16	0.278	1.5	31.4	27.7	15.1	0.621
Q_H	Overall	2315	0.55	27.19	0.572	11.0	36.5	26.1	25.3	0.828
	Daytime	1169	0.41	48.83	0.455	11.7	47.7	38.5	27.8	0.749
	Nighttime	1146	0.12	18.31	0.075	10.4	19.3	18.0	7.0	0.489
Q_E	Overall	2315	0.17	19.73	0.183	-8.1	42.8	39.0	17.0	0.507
	Daytime	1169	0.11	32.69	0.112	-10.1	54.0	50.7	18.2	0.419
	Nighttime	1146	0.01	12.55	0.01	-6.1	27.3	27.2	3.1	0.236

The sky conditions played a significant part in the urban surface energy exchanges. The median daily maxima of Q^* , Q_H , ΔQ_S , surface albedo, and β all present a consistent order from large to small for clear, cloudy, and rainy days because those variables are greatly influenced by the incoming solar radiation, which changes with the sky conditions in the same order. Q_E shows a different order from large to small for rainy, clear, and cloudy days, suggesting that not only abundant rainfall but also strong radiation and high air temperature promote evaporation. The magnitude of $L\downarrow$ on rainy and cloudy days is larger than that of clear days, showing $L\downarrow$ as a function of cloud cover.

The present study discovers some features different from those obtained in dry sub(tropical) climates or temperate regions. The daily maxima of $K\downarrow$ vary more than that of London and Shanghai, and the daytime surface albedo is smaller than that of Los Angeles and Chicago. The mean daytime proportion of Q^* dissipated by Q_H is smaller than most of the other sites, because a high urban density could cause a large ΔQ_S within the canopy and reduce upward-directed Q_H . The proportion of Q^* dissipated by Q_E is larger than that of hot desert climate sites. The mean daytime Q_E/Q^* and β are functions of both vegetation fraction and urban density.

The adaptabilities of NARP, OHM, and LUMPS to the humid subtropical region were confirmed by comparison with field observations. For the whole study period, the predicted Q^* and ΔQ_S have highly positive correlations with their measured values, showing an index of agreement higher than 0.95. The RMSE values of Q_H and Q_E are 36.5 and 42.8 W m⁻², falling within an acceptable range by comparing the validations by Loridan et al. (2011) and Ao et al. (2017).

In the present study, local-scale urban energy balance observations under various sky conditions in the humid subtropical region are presented. The results help us verify and improve parameterizations of the energy exchange over urban surfaces in this region and can be practically beneficial when guiding urban planning and resilient urban designs.

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