# Seasonal variations in the surface energy and CO2 flux over a high-rise, high-density, residential urban area in the East Asian monsoon region

Short Title: Urban surface energy and CO2 fluxes in the East Asian monsoon region

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**Abstract**

Using the eddy covariance method, this study reports the one-year turbulent fluxes of momentum, energy, and CO2 and their seasonal variations over a recently redeveloped high-rise, high-density, residential area in the metropolitan city of Seoul, Korea. The area of study is affected by the Asian monsoon, which is accompanied by lengthy rainy spells and related mid-season depression of solar radiation in the summer. Our analysis shows that the urban surface energy balance and turbulence characteristics show typical urban properties. Unstable conditions dominate all day long, and the storage heat flux (night-time and morning) and sensible heat flux (afternoon) significantly affect the diurnal variations in the urban surface energy balance. Because of the rough urban surface, the turbulence intensities are higher than those previously reported in other cities. The annual CO2 emission rate is approximately 13.1 kg CO2 m−2 yr−1 with traffic, the major source of CO2 (+2.3 μmol m−2 s−1 per 100 vehicles). Ecosystem respiration, including that by vegetation, soil, and humans, becomes dominant in the night-time (00:00–05:00), thus contributing significantly to the annual CO2 budget. Further analysis indicates a unique coupling of urban surface energy partitioning and CO2 emission rates with the seasonal progression of the Asian monsoon: 1) surface albedo has annual minima in late summer when the sun elevation angle is relatively higher and the urban surface condition is wetter than in other seasons; 2) the Bowen ratio ranges from 1.7 (summer) to 7.0 (winter); and 3) CO2 emission rates show seasonal variations with the progress of the summer monsoon.

**Keywords**: urban climate, high-rise residential area, high-density, Asian monsoon, Seoul, surface energy balance, CO2 emission, eddy covariance method

1. **Introduction**

Recently, interest has grown regarding the effects of urbanization on local, regional, and global changes in biogeochemical cycles. With more than one-half of the world population living in cities (UN, 2014), anthropogenic activities in cities can threaten societal sustainability by accelerating environmental changes. By fossil fuel combustion and cement production, about 10 billion tons of carbon in CO2 (Ballantyne *et al.*, 2012) and equivalent waste heat are emitted into the atmosphere annually; most such anthropogenic emissions are closely related to urban metabolisms (Grimm *et al*., 2008). Recent climate change is a major challenge for cities and surrounding areas because they are vulnerable to climate-induced scarcities of water and food, degradation in air quality, and extreme weather, particularly as cities expand. Consequently, the interactions between a city and the climate system require immediate attention and study. The long-term monitoring of urban surface fluxes to the atmosphere will enable us to improve prediction of future weather, climate systems, and their effects on our societies. Direct observations are necessary for developing and evaluating urban-atmosphere exchange models; furthermore, data-based models of urban-atmosphere interactions can be used by policymakers to establish effective policies for climate mitigation and adaptation.

Monitoring of the exchanges of momentum, energy, and mass at the urban-atmosphere interface has received considerable attention in recent decades. The eddy covariance method is one of the most widely used techniques for the direct measurement of surface fluxes. In the last 30 years, the eddy covariance method has developed rapidly, with approximately 50 applications to the study of urban surfaces worldwide (Grimmond and Christen, 2012). Previous studies have suggested the following commonalities of urban surface energy balance (SEB) and CO2 emission rates (*FC*): 1) the sensible heat flux (*QH*) is dominant over the latent heat flux (*QE*), 2) the heat storage term (*dQS*) is important in determining SEB, and 3) the urban surface is a net CO2 source, and *FC* is controlled by traffic counts and vegetation areal fractions.

Most urban flux towers are concentrated in developed countries in Europe and North America. Therefore, previous investigations have not assessed urban surface fluxes extensively regarding their component, magnitude, and temporal variation for developing countries in Asia and Africa. Although more than half of the world’s urbanites live in Asian countries, only a few studies have investigated short-term urban SEB and *FC* in Asian cities, e.g. Tokyo, Japan (Moriwaki and Kanda, 2004); Beijing, China (Liu *et al.*, 2012; Miao *et al*., 2012; Song and Wang, 2012); Singapore (Velasco *et al.*, 2013; Roth *et al*., 2017); Shanghai, China (Ao *et al.*, 2016); Osaka, Japan (Ueyama and Ando, 2016; Ando and Ueyama, 2017); and Seoul, Korea (Hong and Hong, 2016). The lack of directly observed data from developing countries especially in the Asian monsoon region hinders our understanding of the interactions between urban structures and their functions with the environment.

It is rare to study the effects of rapid urban development on the urban microclimate in Asian cities influenced by the Asian monsoon. Hong and Hong (2016) reported on the effects of residential regeneration on the surface heat environment using long-term direct measurements of *QH* and radiative fluxes. Following the urban redevelopment into a compact, high-rise residential building, the urban heat island intensified by approximately ~0.6 oC, and the fractions of *QH*, anthropogenic heat emission (*QF*), and *dQS* increased (Hong and Hong, 2016). However, without *QE*, the SEB was inevitably uncertain, and the *FC* over urban areas was left for future study. In addition, most Asian cities are influenced by the East Asian monsoon system. The Asian monsoon is characterized by heavy precipitation events and tropical cyclones (i.e. typhoons) during the monsoon period, which affects natural ecosystems and their water cycles (e.g. Kwon *et al*., 2010; Hong and Kim, 2011; Hong *et al*., 2014). Some studies reported that, in Asian cities, *QE* was important in the SEB during the summer monsoon season (Moriwaki and Kanda, 2004; Liu *et al.*, 2012; Miao *et al*., 2012; Ando and Ueyama, 2017). In previous urban flux measurement efforts, the role of the Asian monsoon in urban microclimates and *FC* was not investigated extensively. The monsoon period coincides with the main summer growing season for vegetation. Previous studies have suggested the importance of urban vegetation as a regulator for energy and water cycles over urban ecosystems; however, little attention has been paid to the role of urban vegetation on *FC* in this unique region.

With the above background, the main purpose of this study is to report the one-year turbulent exchanges of energy and CO2 over a high-rise, high-density residential area in Seoul, Korea by focusing on their seasonal variations and controlling factors. We highlight the impacts of the Asian summer monsoon on the urban SEB. After the methodology and site description are presented (section 2), the flux measurement results are reported with random error characteristics (section 3). We investigate temporal variabilities of surface fluxes by classifying the observation data into seasons (December–February, winter; March–May, spring; June–August, summer; and September–November, autumn), working days (weekdays, not holidays) and non-working days (weekends and holidays), and daytime (> 0 W m−2 of net radiation) and night-time periods.

1. **Methods**

***2.1. Urban Surface Energy–CO2 Balances***

For the ideal volume of the urban ecosystem, SEBs could be expressed as the following equation (Oke, 1987):

*Q\** + *QF* = *QH* + *QE* + *dQS* + *dQA* (W m−2). (1)

*Q\** is the net radiation estimated by the sum of incoming and outgoing, or reflected, short- and longwave radiation (*K↓*, *K↑*, *L↓*, and *L↑*):

*Q\** = *K↓ – K*↑ + *L↓* – *L↑* (W m−2) (2)

This study presents direct observations of surface albedo (*α* = *K↑*/*K↓*) by a net radiometer, analysed with several potential issues to understand the neighbourhood-scale *α* and its seasonal variability.

Similar to previous studies, this study estimates *dQS* as the residual (*RES*, = *Q*\* – *QH* – *QE*). This approximation can include *QF*, measurement errors, and footprint mismatches. The annual mean *QF* is approximately 20 W m-2 from an inventory estimation (Lee and Kim, 2015).

The urban CO2 budget equation is expressed as (Feigenwinter *et al.*, 2012):

*FC* + *dS* = *C* + *RE* − *P* (μmol m−2 s–1). (3)

Here, *dS*, *C*, *RE*, and *P* are the concentration change of CO2 in the control volume, CO2 emission from fossil fuel combustion, respiration by soil, vegetation, and humans, and CO2 uptake by photosynthesis, respectively. *dS* can be neglected by the stationary assumption of the eddy covariance method; therefore, the observed *FC* is the well-mixed sum of *C*, *RE,* and *P*, representing the neighbourhood spatial-temporal scale in the upwind direction.

***2.2. Site Description***

The flux tower is located in the north-western part of Seoul, Korea (Fig. 1; 37.6350°N, 126.9287°E). The district around the tower was redeveloped in 2009 following the New-Town plan, a representative housing regeneration policy in Seoul and its satellite cities. The total population was approximately 53000 (4600 people km−2). Within the flux footprint area (within 200 m southwest), 60% of land cover is buildings and roads; therefore, the actual population density is approximately 15000 people km-2. For the week of 3–9 November 2014, traffic counts were conducted on a major road near the flux tower (star in Fig. 1), reaching 11835 and 10834 vehicles d−1 on weekdays and weekends, respectively. Within 500 m of the flux tower, buildings, roads, and impervious land cover types are situated on the relatively flat terrain in the south to west directions (135–315°). To the north of the tower (315–45°), vegetated zones are included in the flux footprint. Our analysis in this study is based on the urban area from the south to west direction, but our overall conclusion does not change even if we extend our analysis to all wind directions.

Based on the Local Climate Zone scheme (Stewart and Oke, 2012), the southern part is classified as a compact high-rise (type 1). Within 200 m of the flux tower, the mean horizontal building area fraction is approximately 0.35. The corresponding mean building height (*zH*) is ~18.6 m, and the zero-plane displacement and roughness length are ~11.3 m and ~1.6 m, respectively. The aspect ratio, defined as the ratio of building height to road width (*HWR* hereafter), is about 1.0. The sky-view factor, estimated by airborne light detection and ranging (lidar) imaging, is 0.5. Detailed descriptions of the urban structure parameters are found in Hong and Hong (2016).

***2.3. Climate Condition***

Korea has four distinct seasons, including a hot and humid summer and a cold and dry winter, with mild transition seasons of spring and autumn. The climatological means (1981–2010) for air temperature and precipitation in Seoul are 12.5 °C (−2.4 °C(January), 25.7 °C (August)) and 1450 mm yr−1, respectively. In general, more than 50% of annual precipitation (892 mm in the 30-yr average) is concentrated in the summer season with the East Asian monsoon. These climate conditions are different from those of other Asian cities with reported surface fluxes, particularly regarding 1) intervals of heavy rain in summer, 2) larger seasonal variations in air temperature, and 3) significant depression of solar radiation in the summer monsoon season.

During the study period (March 2015–February 2016), the climate condition in Korea was abnormally hot and dry. In Seoul, the mean air temperature, accumulated precipitation, and solar duration (the period *K*↓ > 120 W m−2) were 13.3 °C (+0.8 °C from 30-year climatology), 806.7 mm (−643.9 mm), and 2598.3 h (+532.4 h), respectively (Fig. 2 and Table 1). Unusually, rain fronts remained in the south of the Korean peninsula during Changma, the intensive heavy rainfall period of June 25th to July 29th. The total rainfall recorded in Seoul was only 221.4 mm, 145 mm less than the 30-year climatology. The beginning of autumn (September 2015) was warm and dry but gradually became humid with southerly winds from the Philippine Sea. Compared with 30-year statistics, the precipitation (solar duration) increased (decreased) by 52.1 mm (44.2 h) in November 2015, unlike the summer season. However, the mean air temperature was 1.7 °C higher than normal, probably because the reduction of longwave cooling by cloud cover was dominant. During the winter season, relative warmth was maintained until late January 2016 with a strong El Niño and positive Arctic Oscillation. Then, a strong cold wave moved southward from the arctic region, and cold weather conditions lasted until the end of February 2016.

***2.4. Instrumentation and Data Process***

*2.4.1. Instrumentation*

The 10-m-high lattice tower was built on the rooftop of a 20-m building. A three-dimensional sonic anemometer and closed-path infrared gas analyser (IRGA) (CPEC200, Campbell Scientific Inc., USA) were installed at the top of the tower for turbulent flux measurements with a 10-Hz sampling rate. Closed-path IRGA is advantageous in having a better retrieval rate for monsoon-affected areas, characterized by intense rain during the Asian summer monsoon and dusty conditions in the spring (Choi *et al.*, 2004; Dias *et al*., 2009; Hong *et al*., 2014). *Q\** was computed by the 10-min averages of *K↓*, *K↑*, *L↓*, and *L↑* as measured by a net radiometer (CNR4, Kipp&Zonen, Netherlands). By Lambert’s cosine law, the 99% source area of the net radiometer was a circle of ~130 m in radius (Schmid, 1997) and a good representation of the surrounding residential environment. All data were recorded using a data-logger (CR3000, Campbell Scientific, USA). At least every three months, the IRGA was calibrated with a standard CO2 gas of 401.1 ppm (CRM No. 112–01–018, Korea Research Institute of Standards and Science) and N2 gas for zero calibration. The measurement system was checked daily via teleconnection, and data were retrieved every two weeks on field trips.

*2.4.2. Data Processing*

Turbulent fluxes were computed by EddyPro software (version 6.2.0, Li-COR, US) with a 30-min averaging period. The magnetic declination angle (8°15’W on May 1, 2015, changing by 0°03’W yr−1) was considered to calculate the wind direction. Double rotation, spike removal (Vickers and Mahrt, 1997), and spectral correction (Moncrieff *et al.*, 2004; Fratini *et al.*, 2012; Horst and Lenschow, 2009) were applied. In the post-processing, outliers in the 30-min CO2 fluxes were discarded, and negative (absorption) fluxes during night-time were excluded from analysis (Papale *et al.*, 2006; Hong *et al.*, 2009; Hong and Hong, 2016). After quality control, 98.0% of radiative fluxes, 92.4% of *QH*, 89.5% of *QE*, and 93.7% of *FC* data were available for analysis. For convenience, this study uses *LST* (Local Standard Time), which is 9 h ahead of *UTC* (Universal Time Coordinated).

The stability parameter, *ζ*, was computed to quantify atmospheric stability as follows:

*ζ* = (*zm* – *zd*)*L* = (*zm* – *zd*), (4)

where *zm* is the measurement height from the ground, and *zd*, *L*, *u\**, *w*, *θv*, *k*, and *g* are the zero-plane displacement height by 45° intervals (Hong and Hong, 2016), the Obukhov length, friction velocity, vertical wind speed, virtual temperature replaced with sonic temperature, von Kármán constant (= 0.4), and gravitational acceleration (= 9.821 m s−2), respectively. An overbar denotes the temporal mean, while the prime symbol denotes a perturbation from the mean. The estimated *ζ* is divided into four categories: stable (*ζ* > 0.1), near-neutral (0.1 > *ζ* > –0.1), unstable (–0.1 > *ζ* > –0.5), and strongly unstable (–0.5 > *ζ*). The normalized standard deviations of *w* (*Φw*) and temperature (*ΦT*) were tested to check the data quality and the turbulence characteristics:

*Φw* = *σw*/*T\** = *σw* / (/*u\**) = , (5)

*ΦT* = *σw*/*u\** = .(6)

Characterizing the random error (*ε*) of the measured fluxes is essential for model validation, parameter optimization, and estimating statistical confidence in the measured fluxes. This study quantifies the total random uncertainty in the measured turbulent fluxes and its covariant properties with meteorological variations by employing the daily differencing approach (Hollinger and Richardson, 2005; Richardson *et al*., 2006). If a measurement flux (*x*) pair of two successive days (*x1* = *F*+*ε1*, *x2* = *F*+*ε2*, and *F* is the true flux) are under equivalent environmental conditions, the standard deviation of random error (*σ*(*ε*)) can be written as:

*σ*(*ε*) = *σ.* (7)

For this daily differencing method, similar environmental conditions are assumed for 24-h differences in downward shortwave radiation within 100 W m−2, air temperature within 2 °C, and wind speed within 0.5 m s−1 in the same wind direction sector (135–315°). More information on the random flux error estimation is found in Hollinger and Richardson (2005).

1. **Results**

***3.1. Wind and Turbulence Characteristics***

Figure 2 shows the climate conditions observed at the site throughout the study period. The daily mean wind speed is ~1 m s−1, with higher values in spring and summer than in autumn and winter (Fig. 2d). The mean diurnal courses of wind direction show the local circulation of the typical warm and cold breezes induced by thermal contrast around the site (Fig. 1). The land covers of areas to the south and north of the tower are high-rise residential area and forest, respectively, inducing an observed thermal gradient in the diurnal course between them. During the daytime, the wind comes from the urban area (180–270°; SSW and WSW), which is warmer than the forested area; the prevailing wind direction gradually changes to the north (315–45°; NNW and NNE) after sunset. Near-zero wind is observed during these daily transition periods. Throughout the year, this local breeze due to the thermal contrast around the tower dominates, except in rainy conditions. During rainy conditions, the observed wind direction follows the synoptic weather condition rather than local circulation, probably because of the weakened thermal gradient by the depression of radiation and increased evaporative cooling of vegetation in the summer growing season. The overall seasonal change in the local breeze is small, but the pattern occurs more frequently in summer.

The atmosphere is mainly unstable with a strong southerly wind during the daytime (Fig. 4b); the fraction of stable conditions is relatively small (Fig. 3 and Fig. 4a). In this study, 56.5% of data reflect unstable conditions (27.8% for strong instability, 28.7% for moderate instability), while stable and near-neutral conditions comprise 19.4% and 24.1%, respectively. The fraction of unstable conditions during night-time (19:00–07:00) is 40.9%, which is larger than the night-time stable condition of 32.5%. This indicates that the nocturnal urban boundary layer remains unstable because of *dQS* and *QF*, as reported in previous studies (e.g. Christen and Vogt, 2004).

The turbulence intensity (*σi*/*U*, where *I* = *u*, *v*, or *w*, *σ* is the standard deviation, and *U* is the mean wind speed) and the integral turbulence characteristics of wind velocity (*σi*/*u\**) are necessary to understand atmospheric diffusion in the atmospheric boundary layer; they are necessary for various purposes, including quality control of the observed data and surface flux estimations. The turbulence intensities, *σu*/*U*, *σv*/*U*, and *σw*/*U*, are 0.54±0.18 (mean ± standard deviation), 0.55±0.18, and 0.39±0.12 in near-neutral conditions, respectively. The ratio of *u\** to *U* is 0.24±0.01, corresponding to a drag coefficient of 0.0576 (Fig. 5a). These turbulence intensities are larger than those proposed by Roth (2000) based on the empirical relationships of *σi*/*U* and *u\*/U* using the ratio between the measurement height and mean building height (*zm*/*zH*) (see Table 4 in Roth (2000)). This discrepancy may arise from the difference in the definition of mean wind speed, because the mean wind vector, *U* (), used in this study is generally smaller than the mean wind speed, () (Wilson *et al*., 1982; Hong *et al*., 2002). Another possibility arises from the sharp decline in turbulence intensity with height due to a lack of data for more rugged urban surfaces, such as high-rise buildings like those in this study and for *zm*/*zH* of < 1.5 in previous studies.

The integral turbulence characteristics of wind velocity, *σu*/*u\**, *σv*/*u\**, and *σw*/*u\**, are 1.91±0.45, 1.88±0.33, and 1.35±0.20, respectively, in near-neutral conditions. Unlike the turbulence intensities, these values are comparable with those reported in previous studies of urban areas and natural vegetation, probably because the smaller values of *σi*/*U* and *u\*/U* tend to cancel out in integral turbulence characteristics (Raupach *et al*., 1998; Roth, 2000; Hong *et al*., 2002).

Figures 5b and c show *Φw* and *ΦT* as functions of *ζ*. The similarity constants *C1*, *C2*, *C3*, and *C4* in equations (5) and (6) are determined as *C1* = 1.16, *C2* = 4.11, *C3* = 1.10, and *C4* = 0.12. Previous studies reported similar values in the ranges of 1.12–1.30, 2.09–3.00, 0.95–1.14, and 0.030–0.085 for *C1*, *C2*, *C3*, and *C4*, respectively (e.g. Tillman, 1972; Panofsky *et al.*, 1977; de Bruin *et al.*, 1993; Kaimal and Finnigan, 1994; Roth, 2000; Toda and Sugita, 2003; Choi *et al.*, 2004; Hong *et al*., 2004).

***3.2. Random Flux Error***

For the natural ecosystem, random errors in flux measurements have leptokurtic double-exponential (Laplacian) distributions rather than normal (Gaussian) distributions (Hollinger and Richardson, 2005; Richardson *et al*., 2006). Previous studies also reported that the random flux error was heteroscedastic, implying that the standard deviation of the random error (σ(*ε*)) increased linearly with increasing measured flux magnitude. The random flux error has not been reported for urban areas.

Our results suggest that the statistical properties (mean, standard deviation, skewness, and kurtosis) of the random flux error in the urban residential area are similar to those in natural environments (Fig. 6 and Table 2). The random flux error shows a peaked distribution rather than a normal distribution (Figs. 6a–c, and kurtosis in Table 2). Slopes (0.11, 0.31, and 0.24 for *QH*, *QE*, and *FC*) and offsets (15.16 and 8.80 for *QH* and *QE*) of the random flux error are similar to those reported for forest canopies (slope: 0.16, 0.23, and 0.63; offset: 19.7, 15.3, and 0.62) and grassland (slope: 0.07, 0.16, and 0.30; offset: 17.3, 8.1, and 0.38) (Richardson *et al*., 2006), excepting the offset of *FC* (3.97). The seasonality of σ(*ε*) is proportional to the magnitude of the measured flux; however, the relative error (σ(*ε*)/ in Table 2) shows relatively smaller seasonality. The σ(*ε*)/ of *QH* (0.28) is lower than those of *QE* (0.83) and *FC* (0.80). We speculate that these larger σ(*ε*)/ in *QE* and *FC* are related to error propagation by the two instruments used (a sonic anemometer and IRGA), while *QH* is measured only using a sonic anemometer. In addition, the source and sink distributions of *QH* are relatively more homogeneous than those for *QE* and *FC* (e.g. buildings, soil, and vegetation), which induces greater sensitivity to meteorological conditions.

The relatively larger offset of the random error of *FC* (i.e. σ(*ε*) at *FC* = 0) at the site seems to be related to the assumptions applied in the daily differencing approach. Indeed, zero *FC* appears at least twice a day in a natural ecosystem (i.e. around sunrise and sunset), but such conditions do not usually occur in high-density urban areas. Instead, irregular changes in anthropogenic emissions, such as traffic volume, can occur during equivalent meteorological conditions, violating the assumption in the σ(*ε*) estimation. In this respect, our result needs careful interpretation as an upper limit for random flux error. The daily differencing method is practically applicable, but previous studies found that the daily differencing method generally overestimated the σ(*ε*) relative to the independent two-tower method and the model residual method, because it is difficult to ensure identical climate conditions (Richardson *et al*., 2006; Dragoni *et al*., 2007). Notably, traffic amounts can cause increases in σ(*ε*) of *FC* in urban areas, because the traffic volume is not entirely dependent on meteorological conditions, even at the same time of day.

***3.3. Surface Radiative Balance***

*3.3.1. Radiative Fluxes and Albedo*

Figures 7a–c show seasonal changes in the diurnal variability of surface radiative fluxes. The daily peak times of *K*↓, *K*↑, and *Q\** are around noon, but *L*↓ and *L*↑ reach daily maxima at 14:00 local time when the surface temperature reaches its daily maximum. In the daytime, the variability of *Q\** is determined by *K*↓. The magnitude of night-time *Q\** depends on the longwave cooling.

The sun elevation angle reaches its annual maximum in summer, but the annual maximum of *K*↓ does not appear in summer, and the longwave cooling rate is minimized during the summer monsoon season because of the lengthy rainy spells (Hong and Kim, 2011; Hong and Hong, 2016). The *K*↓ gradually decreases from spring to winter, and the mean longwave cooling rates are approximately −78, −56, −62, and −65 W m−2 in spring, summer, autumn, and winter, respectively (Table 3).

To the best of our knowledge, no reports exist regarding the seasonal variation in surface albedo (*α*) in urban areas. Typical *α* in vegetative areas shows its annual maximum in the growing summer season, corresponding to the annual maximum of the leaf area index, because more solar radiation is reflected, except for photosynthetically active radiation (e.g. Brest, 1987; Song, 1999; Rechid *et al.*, 2009). However, the observed *α* in urban areas is lower in late summer and higher in winter (Fig. 8a). Urban *α* is strongly affected by several factors, including the sun elevation angle, surface wetness, vegetation phenology, land cover fraction, urban structure, and materials. Among these factors, the land cover fraction and urban structure do not change with the season. Phenology cannot explain our observed variations, like those noted in other studies in natural forest canopies, and snow is also of secondary importance since there were only three days of snow. Here, we note two possible reasons for the observed seasonal changes in *α*: the effects of moisture on building surfaces and soil and that of the sun elevation angle on *α*.

Typically, *α* decreases with an increasing sun elevation angle; *α* decreases particularly sharply between zero and 30° (White *et al*., 1978; Aida 1982; Christen and Vogt, 2004; Grimmond *et al*., 2004; Balogun *et al*., 2009; Bergeron and Strachan, 2012; Kotthaus and Grimmond, 2014). Our data show the same dependency of *α* on sun elevation angle (Fig. 9). Indeed, the mean sun elevation angle in daytime is smaller than 30° in the fall and winter; consequently, *α* in these two seasons is larger compared to that in summer.

Furthermore, our scrutiny reveals that seasonal changes in surface moisture conditions with the seasonal progression of the East Asian monsoon are related to *α* seasonality (Fig. 8c). Figure 8c shows *α* with accumulated solar radiation after precipitation events as a measure of surface moisture. This provides information on the surface moisture; it is practically infeasible to retrieve surface moisture in urban areas. Some studies have used the elapsed time after precipitation events (e.g. Kotthaus and Grimmond, 2014). In this study, the accumulated solar radiation is used instead of the elapsed time because the latter depends on the timing of the beginning and end of a precipitation event. *α* clearly increases with increased accumulated *K*↓ after precipitation events, showing an equilibrium value of 0.185 after one clear day (i.e. 20 MJ m−2 of accumulated *K*↓). Precipitation during the summer monsoon season accounts for approximately half of the total annual precipitation at 397.9 mm and 49.3%; this wet summer period promotes smaller *α* in summer compared to that in other seasons, as mentioned above, consistent with the observed seasonal variation in *α*. Our results highlight that this urban canyon wetting feedback with *α* significantly affects the surface radiative balance and SEB in Asian cities influenced by monsoon systems.

*3.3.2. Footprint of a Radiometer*

The footprint mismatch between a hemispheric radiometer and the turbulent flux footprint is important in this analysis. Figure 9 shows the observed *α* with sun elevation angles and the modelled dependency of *α* on the aspect ratio (*HWR*). The model simulation in Figure 9 is based on the urban canyon radiative transfer scheme proposed by Harman *et al.* (2004) and Porson *et al.* (2010). The observed upward radiative fluxes are viewed differently from actual urban structures when measured by a hemispheric radiometer because of radiometer footprint weighting (Adderley *et al*., 2015). The footprint of a hemispheric radiometer obeys Lambert’s cosine law (Schmid, 1997), and, therefore, a building structure near a radiometer has a relatively greater contribution to the radiative flux measurement per unit area than structures far from the instrument. This means that urban canopy structures, such as *HWR*, embedded in the observed radiative fluxes may differ from the actual urban structure around the flux tower. The *HWR* value at the study site is 1.0 based on aerial lidar imaging around the flux tower (Hong and Hong; 2016). However, *HWR* weighted by the radiative flux footprint of the hemispheric radiometer is much smaller than 1 from the aerial lidar image, indicating that the observed upward radiative fluxes are reflected more than the actual amount coming from inside of the urban canyon. Consequently, the observed *α* could be approximately 10% smaller than the actual *α*, thereby leading to overestimation of *Q\** and the surface energy imbalance. This bias corresponds to ~2% of *K*↓ or 20 W m−2 at most around noon in clear conditions in spring and summer. The modelled *α* is sensitive to *HWR*, and the model reproduces the observed *α* when using the radiative flux footprint-weighted *HWR*. This indicates that footprint mismatches in the hemispheric radiometer can contribute to uncertainty in the SEB, unless it is properly considered in the data analysis and modelling interpretation.

***3.4. Surface Energy Balance***

*3.4.1. Seasonal Variations*

Urbanization favours *QH* over *QE* by enhancing the fraction of impervious surfaces. Like those in other cities, our study site shows *QH* values larger than *QE* throughout the year (Fig. 7d–e and Table 3). However, evapotranspiration is not negligible even in the high-rise, high-density of tall buildings because of vegetation between the buildings and the summer monsoon. In addition, *QH* and *QE* show different seasonality as the monsoon progresses. *QH* gradually decreases from the spring to winter season (Fig. 7d and Table 3), whereas *QE* is maximized in the rainy summer monsoon season (Fig. 7e and Table 3) and approaches zero in the cold and dry winter season (Figs. 2a–b and Table 1). Consequently, the Bowen ratio (*β* = ∑*QH*/∑*QE*) is lower in summer and higher in winter (Fig. 10). The seasonal mean daytime *β* values are approximately 4.0, 1.8, 2.7, and 8.2 for spring, summer, autumn, and winter, respectively. Other Asian cities have not reported exact seasonal means of *β* but have reported values of approximately 2–4 in Tokyo, Japan (Moriwaki and Kanda, 2004), 2–4 in Shanghai, China (Ao *et al*., 2016), and ~1.5–3 in Osaka, Japan (Ando and Ueyama, 2017). In comparison with other Asian cities, the *β* at our site shows similar changing trends but a larger seasonal range, attributable to the greater seasonal difference in precipitation at our site. The wintertime *β* value, in particular, is higher than those in other studies because January 2016 was both drier and colder than normal; the opposite situation occurred in summer, as summer 2015 was drier than the climate average (Table 1).

*3.4.2. Diurnal Variation*

Figure 7 shows that the peak times of both turbulent heat fluxes (*QH* and *QE*) are delayed (13:30–14:00) relative to the peak of *Q\** around noon. This phase-shift between turbulent heat fluxes and *Q\** was also reported for several other cities in various climate zones (Grimmond and Oke, 1995; Oke *et al*., 1999; Nemitz *et al*., 2002; Christen and Vogt, 2004; Grimmond *et al*., 2004; Lemonsu *et al*., 2004; Moriwali and Kanda, 2004; Offerle *et al*., 2005; Coutts *et al*., 2007; Balogun *et al*., 2009; Ramamurthy and Pardyjak, 2011; Kotthaus and Grimmond, 2014). However, the behaviours of this time lag were inconsistent in previous studies. For example, the phase-shift was reported only in *QH* (Grimmond and Oke, 1999; Newton *et al*., 2007; Masson *et al*., 2008; Ao *et al*., 2016), only in *QE* (Grimmond and Oke, 1995; Ando and Ueyama, 2017), or lacking in both *QH* and *QE* (Grimmond and Oke, 1995; Christen and Vogt, 2004; Coutts *et al*., 2007; Frey *et al*., 2011; Velasco *et al*., 2011; Goldbach and Kuttler, 2013; Ward *et al*., 2013).

For the time lag of both turbulent fluxes, the daily peaks of both the vapor pressure deficit (*VPD*)and thermal difference between the urban surface and the overlying air, which drives *QH* and *QE*, appears in the afternoon, about 1–2 h after the *Q\** maximum. Furthermore, the major sources of *QE* (e.g. trees, grasses, and soil) are affected by building shadows in the daytime, because they are located at road edges under buildings within the urban canyon, while the major sources of *QH* are mainly distributed on roofs, walls, and roads. The shadow effect on *QE* may contribute to the observed peak-time delay in *QE*. Indeed, the two tallest buildings on the site are located at the eastern end, so shadows emerge in the morning inside the urban canopy (not shown here).

The ratios of *QH* and *QE* to *Q\** (*QH*/*Q\** and *QE*/*Q\**) show similar diurnal variations with monotonic increases and similar slopes from morning to afternoon (Fig. 11b–c), such that *β* is constant and *dQS*/*Q\** decreases monotonically throughout the daytime (Fig. 11a). This result suggests typical variations in *dQS*/*Q\** during the day. In the morning, most *Q\** is used to heat buildings and roads, and, in the afternoon, the urban surface is hot enough, so *dQS*/*Q\** decreases accordingly. Indeed, the relationship between the residual and *Q\** shows a clockwise hysteresis pattern (Fig. 11e), which is typically observed in urban areas (Grimmond and Oke, 1999; Rigo and Parlow, 2007; Velasco *et al*., 2011; Ramamurthy *et al*., 2014; Hong and Hong, 2016). During the night-time, near-zero values of nocturnal turbulent heat fluxes (i.e. unity of *dQS*/*Q\**) indicates a balance between the longwave radiation and *dQS*.

***3.5. CO2 Concentration***

The observed diurnal CO2 concentration shows a morning peak and then decreases to the minimum in late afternoon hours (Fig. 13a). The peak in the morning is well matched with the traffic volume around the tower; the smaller values in the afternoon are associated with the higher planetary boundary layer height. Such diurnal patterns have been reported in other cities (Reid and Steyn, 1997; Grimmond *et al.*, 2002; Velasco *et al.,* 2005; Kumar and Nagendra, 2015; Crawford *et al.,* 2016; Schmutz *et al.,* 2016; Roth *et al*., 2017). During the study period, the mean concentration is 414.8 ppm. The daily amplitude, or the difference between the maximum and minimum, is 18.4 ppm (4.4% of the mean concentration). The background CO2 concentration at Mauna Loa is 401.4 ppm throughout the study period (NOAA, 2018).

In the mid-latitudes of the northern hemisphere, CO2 concentrations are generally higher in winter than in other seasons, because more fossil fuel combustion is used for heating while vegetation absorbs less CO2. Similarly, our data show that the seasonal mean CO2 concentration is the highest in winter at 424.3 ppm (with a daily maximum of 524.7 and a 15-day mean of 486.3 ppm) but does not substantially decrease during the summer season (Fig. 12). The CO2 concentration increases during the summer monsoon season. We speculate that such a pattern in summer is associated with the reduced photosynthesis during a depression of the solar radiation concurrent with the summer monsoon season (Kwon *et al*., 2010; Hong and Kim 2011). This indicates that the observed CO2 concentration is seasonally controlled by the intensity and duration of the summer monsoon, as well as by anthropogenic emission (i.e. vehicular traffic) and the evolution of the planetary boundary layer (i.e. dilution and accumulation).

***3.6. CO2 Flux***

Figure 13b shows the seasonally averaged diurnal variation in CO2 fluxes (*FC*). The seasonal mean *FC* are 10.3, 7.5, 8.9, and 10.9 μmol m−2 s−1 (39.1, 28.4, 33.7, and 41.6 gCO2 m−2 d−1) for spring, summer, autumn, and winter, respectively (Table 4). The total CO2 emission in summer (about 2.6 kgCO2 m−2) is 1.2 kgCO2 m−2 less than that in winter (3.8 kgCO2 m−2). This difference comprises approximately 71% of the annual net ecosystem production in East Asian temperate forests (1640±630 gCO2 m−2 yr−1; seven sites with annual mean air temperatures of 10–16 °C as reported in Kato and Tang (2008)). We speculate that the seasonality of *FC* is mainly associated with vegetation phenology, which covers approximately 32% of the land surface around the flux tower, rather than with local heating systems. The district heating system for the apartment complex utilizes hot-water transport from a power plant far outside the flux footprint, and thus does not contribute to the observed seasonality of *FC*.

The summertime *FC* of 7.5 μmol m−2 s−1 is comparable with the values obtained from the relationship between the summertime *FC* and the plan area fraction of buildings (*λB*) reported in other urban areas by Grimmond and Christen (2012) and Christen (2014). The annual CO2 emission rate at the site is 13.1 kgCO2 m−2 yr−1, which is also comparable with those in other cities reported in previous studies (Ward *et al*., 2015).

The *FC* difference between working and non-working days is similar to the seasonal variation (Figs. 13c–d, Table 4). On working days, the mean *FC* is 10.1 μmol m−2 s−1 (38.5 gCO2 m−2 d−1), which is 29% higher than that on non-working days (7.8 μmol m−2 s−1 = 29.7 gCO2 m−2 d−1). The nocturnal *FC* is similar on working and non-working days; most of the difference is explained by the reduction in daytime anthropogenic activity from lower traffic volumes on non-working days (Fig. 14a).

Figure 14a shows the mean diurnal patterns for vehicular traffic volume (vehicles per 30-min) during the traffic survey period of November 3–9, 2014. In the morning, the traffic volume on working days is almost twice that of non-working days. This is consistent with the observed diurnal pattern of *FC*, indicating a strong dependency of *FC* on the traffic volume. Similarly to previous studies from several other cities (Nemitz *et al*., 2002; Soegaard and Møller-Jensen, 2003; Vesala *et al*., 2008; Velasco *et al*., 2009; Järvi *et al*., 2012), our site shows a linear relationship between the traffic load (*Tr*) and *FC* (Fig. 14b):

*FC* = 0.023 *Tr* + 3.5 (unit: μmol m−2 s−1; *r*2 = 0.83). (8)

The slope of equation (8) indicates that the observed *FC* is increased by approximately 2.3 μmol m−2 s−1 for every traffic volume increase of 100 vehicles in 30-min. This slope is consistent with the emission inventory data for road vehicles. In the study area, the vehicular speed limit is 30 km h−1 because all roads are assigned as children’s protection areas. Based on the inventory data, the CO2 emission per vehicle per kilometre of travel at 10–30 km h−1 is approximately 300 gCO2 km−1 (= 6.82 mol km−1; Kim *et al.* (2011)), which is approximately twice the emission rate at high speeds (> 40 km h−1). Therefore, for an increase in traffic by 100 vehicles, the increase of *FC* on the road is 253 μmol m−2 s−1 (= 300 gCO2 km−1 vehicle-1 1/44 g mol−1 10−3 m km−1 106 mol μmol−1 100/1800 vehicle s−1). Considering the fraction of main roads (~10%) and the mean road width (~10 m) in the study site, these inventory data estimate 2.53 μmol m−2 s−1 per 100 vehicles, consistent with the observed slope in equation (8).

The magnitude of the intercept in equation (8) (i.e. 3.5 μmol m−2 s−1) is smaller than that of the city centre of Edinburgh in the UK (11.7 μmol m−2 s−1; Nemitz *et al*., 2002) and larger than that of Helsinki in Finland (0.3–1.1 μmol m−2 s−1; Vesala *et al*., 2008; Järvi *et al*., 2012). The intercept of the regression represents non-traffic CO2 emissions, such as ecosystem respiration (*RE*) of vegetation, soil, and humans in urban areas. Vegetative (*REV*) and human (*REH*) respiration are functions of air temperature (Davidson *et al.*, 2006) and population density (Moriwaki and Kanda, 2004; Velasco and Roth, 2010; Ward *et al*., 2013; 2015), respectively. To quantify the contributions of both respiration sources, we add the constant term (*y0*) for *REH* to a van ’t Hoff-type *REV* function (van ’t Hoff, 1898; Davidson *et al.*, 2006; equation 9a):

*RE* = *REH* + *REV* = . (9a)

The observed *FC* during 00:00–05:00 *LST* is selected to avoid the contribution of traffic emissions, because the traffic amount is less than 100 vehicles during this period (Fig. 14a). Using this nocturnal *FC*, the temperature response curve is fitted to equation (9a) (Fig. 14c):

*RE* = (*r*2 = 0.61). (9b)

The coefficients of *y*0, *a*, *b*, and the corresponding *Q*10 (= ) are 2.33, 0.025, 0.18, and 6.0, respectively. The exponential respiration curve reproduces the nocturnal urban respiration well (*r*2 = 0.61). Notably, the fitted *REH* of 2.33 is comparable with the *REH* value of 2.1 μmol m−2 s−1 estimated from the population density (~15000 people km−2) and human metabolism data (2.1 μmol m−2 s−1 = 12.4 mol d−1 = 11 times min−1 1440 min d−1 0.5 ℓ time−1 3.5% 1/22.4 mol ℓ−1) (Prairie and Duarte, 2007; West *et al*., 2009). This result suggests that the estimation of *REH* is a good rule-of-thumb for CO2 source partitioning in urban areas, despite the simplistic approach and uncertainties (Velasco and Roth, 2010).

Our findings also indicate that *RE* is significant for *FC* from midnight to dawn (00:00–05:00) and that vehicular traffic is the dominant source of CO2 for the rest of the day, at approximately +2.3 μmol m−2 s−1 per 100 vehicles. *REH* is likely to remain constant throughout the year; by contrast, *REV* is larger than *REH* in summer (mean *Tair* > 20 °C) but smaller in winter because of its strong dependency on *Tair*. In this study, our statistical and observational data were limited, so additional analysis should be performed using longer collection periods and data with greater detail.

1. **Summary and Conclusions**

Using the eddy covariance method, this study reported the one-year surface fluxes of energy and CO2 to examine the features of urban-atmosphere exchange and the controlling factors thereof over a high-rise residential area in Seoul, Korea, which is affected by the East Asian monsoon system. Our study outlines urban-climate feedback in monsoon-affected Asia by reporting several key findings regarding energy and CO2 exchange at the interface between high-density residential areas and the atmosphere.

The ruggedness of high-rise urban structures induces significantly higher turbulence intensity (*u\**/*U*) and surface drag coefficients relative to those from previous studies in other urban areas. For one year, a warm–cold breeze circulation is consistently observed with diurnal variations, and unstable conditions dominate. Random flux error (σ(*ε*)) is quantified using the daily differencing approach, and our analysis suggests that the statistical properties and seasonality of σ(*ε*) at urban sites show properties similar to leptokurtic double-exponential distributions, as do previous results from natural ecosystems.

The urban SEB is strongly influenced by the summer monsoon, causing substantial changes in *α* and *β*. The observed *α* shows the annual minimum (~0.17) and maximum (~0.20) in late summer and winter, respectively. Our investigation strongly suggests that this seasonal variation in *α* is associated with changes in the sun elevation angle and soil moisture with the progress of the summer monsoon. Furthermore, the *β* shows seasonality similar to that of *α*, ranging from 1.7 in summer to 7.0 in winter. This seasonality of *α* and *β* in urban areas is unique to East Asian urban areas affected by the summer monsoon. Annual mean *α* is generally assigned in urban canopy models; this prescription will eventually underestimate (overestimate) *Q\** in summer (winter) in urban areas in the Asian monsoon region through the bias of the *α* in the models, unless the monsoon influence is considered.

Turbulent heat flux maxima are delayed to 13:30–14:00 compared to that of *Q\** around noon in their diurnal courses. Our investigation indicates that the *VPD* and thermal contrast at the urban-atmosphere interface mainly control this observed diurnal variation in turbulent heat fluxes. Notably, the *VPD* and thermal contrast change as the Asian monsoon progresses. Furthermore, our findings indicate that the heterogeneity between *QH* and *QE* contributes to the observed peak-time delay in *QE*. *dQS* is important in regulating the partitioning of *Q*\* into turbulent energy fluxes. In the morning, most of *Q\** is partitioned into *dQS*, but this fraction steadily decreases during daytime. Consequently, the peak times of *QH* and *QE* are in the afternoon (13:30–14:00), while the peak time of *dQS* appears in the morning. Overnight, *dQS* is balanced with net longwave radiation, while other components are small.

The observed CO2 concentration shows a bimodal diurnal pattern with rush-hour car emissions and the evolution of the planetary boundary layer. The summer monsoon also clearly affects the seasonal variation in the CO2 concentration and fluxes. The mean annual CO2 concentration is ~414.8±9.2 ppm. The annual CO2 emission rate is ~13.1 kgCO2 m−2 yr−1. The total seasonal emission shows the distinct role of urban vegetation; the mid-summer depression of CO2 uptake in the monsoon season controls the temporal variability in CO2 emissions. In the summer, CO2 emission is 2.6 kgCO2 m−2, 1.2 kgCO2 m−2 smaller than winter emissions (~3.8 kgCO2 m−2). The observed *FC* is strongly dependent on vehicular traffic (+2.3 μmol m−2 s−1 per 100 vehicles), while *RE* is significant during night-time. *REH* is estimated as ~2.1 (based on inventory data) to 2.33 μmol m−2 s−1 (based on observed *FC*), and a temperature-dependent equation reproduces the observed nocturnal *REV* well. The *REV* shows strong seasonal variation, approaching zero in winter and reaching 4 μmol m−2 s−1 in summer. In the study area, a district heating system is used to heat the buildings, and, therefore, CO2 emissions from local heating are negligible. In the studied region, the difference between working and non-working days is comparable with the seasonal variation in *FC* via the reduction of traffic volume.

The collected observation data help to fill a gap in the current understanding of the urban surface processes in megacities located in East Asian monsoon-affected areas. Our observational study indicates that surface energy partitioning and carbon exchanges in high-rise residential areas in the Seoul metropolitan area are generally similar to those in other mid-latitude urban areas. However, our findings emphasize the effects of the summer monsoon on the urban SEB in the mid-latitude regions, which has not been seriously investigated in previous studies. Caution must be used in modelling these unique properties of SEB and carbon exchanges by urban canopy models in monsoon-affected Asia.

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**Table Captions**

**Table 1.** Monthly mean air temperature (*Tair*; unit: °C), accumulated precipitation (unit: mm), and solar duration, compared to the 30-yr (1981–2010) average climatological value.

**Table 2.** First four moments of random flux error (*ε*) for *QH*, *QE*, and *FC*, and the linear relationship (Figs. 6d–f) between random flux error CO2 (*σ*(*ε*)) and the magnitude of the measured flux (). Only data from the south direction (135–315°) are used.

**Table 3.** Daily (24-h), daytime (*Q\** > 0 W m−2), and night-time mean observed energy fluxes (unit: W m−2), which are down/upward short/longwave radiation (*K↓*, *K↑*, *L↓*, *L↑*), net radiation (*Q\**), sensible heat flux (*QH*), latent heat flux (*QE*), and the residual, with standard deviation values for each season. Only data observed from apartment areas (180–270o) are used.

**Table 4.** Daily (24-h), daytime (*Q\** > 0 W m−2), and night-time mean CO2 flux (*FC*; unit: μmol m−2 s−1) and standard deviation values for all, working, and non-working days. Only data observed from apartment areas (180–270o) are used.

**Figure Captions**

**Figure 1.** (a) Aerial photograph around the flux tower (●) with the accumulated source area for surface fluxes (contour; method in Hsieh *et al*., 2000) and the location of the traffic survey (★). (b) The location of the flux tower within South Korea is shown with urban land cover (map from GRUMP version 1).

**Figure 2.** Climate conditions for March 2015–February 2016: (a) air temperature (*Tair*; unit: °C) with the 30-year (1981–2010) climatology values (solid line: mean, dashed lines: minimum and maximum), (b) 30-min and accumulated precipitation (*Pr*; unit: mm; solid line: study period, dashed line: climatology value), (c) vapor pressure deficit (*VPD*; unit: hPa), and (d) mean wind speed (*U*; unit: m s−1). Grey and black dots indicate 30-min and daily mean values, respectively.

**Figure 3.** The wind frequency distribution of (a) spring, (b) summer, (c) autumn, and (d) winter. The dominant wind directions were N and SW from local circulations (mountain–valley breeze).

**Figure 4.** Mean diurnal courses of (a) wind direction and (b) stability conditions for March 2015–February 2016. The stability is divided into four regimes: stable (*ζ* > 0.1), near-neutral (0.1 > *ζ* > –0.1), unstable (–0.1 > *ζ* > –0.5), and strongly unstable (–0.5 > *ζ*). The stability parameter ζ is defined as (*zmzd*)/*L* using the value of *zd* by wind direction for each 45° interval (Hong and Hong, 2016).

**Figure 5.** (a) *u\** vs. *U* as a box plot (box: median, 25th, and 75th; whisker: 10th and 90th; symbol: 5th and 95th percentiles) and normalized standard deviations of (b) vertical velocity *w* and (c) temperature as a function of *ζ* (). Only data from the apartment area (180–270°) are used.

**Figure 6.** The frequency distribution of the random flux error (*ε*) for (a) *QH*, (b) *QE*, and (c) *FC*, and (d)–(f) the scaling of each random flux error (*σ*(*ε*)) with the flux magnitude. Only data from the south direction (135–315°) are used.

**Figure 7.** Seasonal diurnal pattern of all surface energy fluxes (unit: W m−2), which are (a)–(b) down/upward short/longwave radiation (*K↓*, *K↑*, *L↓*, *L↑*), (c) net radiation (*Q\**), (d) sensible heat flux (*QH*), (e) latent heat flux (*QE*), and the residual (*RES*). Figure represents the median, interquartile (box), 5th and 95th percentile (whiskers), and mean values (black dots). Only data from the apartment area (180–270°) are used.

**Figure 8.** (a) Daily mean albedo (black cross) with annual mean value (0.185; grey line) and 30-min precipitation (grey vertical bar), (b) sun elevation angle, and (c) accumulated solar radiation since rainfall. The boxes in (b) and (c) represent interquartile values (median, 25th, and 50th ranked values), and whiskers show 10th and 90th percentile ranked values.

**Figure 9.** (a) The modelled albedo for various building aspect ratio (HWR) values and (b) the footprint of the radiometer (solid line) and estimated HWR from digital elevation model data (dashed line).

**Figure 10.** Daytime (*Q\** > 0 W m−2) Bowen ratio (*β*=∑*QH*/∑*QE*; black dot) and daily precipitation (grey bar; unit: mm d−1). Only data from the apartment area (180–270°) are used.

**Figure 11.** Seasonal mean diurnal patterns of observed (a) Bowen ratio (*β*), (b) *QH*/*Q\**, (c) *QE*/*Q\**, (d) residual to *Q\** (*RES*/*Q\**), and (e) hysteresis curve between residual and *Q\**. Only data from the apartment area (180–270°) are used.

**Figure 12.** Seasonal variation in the CO2 concentration. Grey dot and black line are the CO2 concentration observed at the EunPyeong station (EP) and its 15-day moving average, respectively. Dotted line indicates the CO2 concentration observed at Mauna Loa, Hawaii (MLO) during the study period. Only data from the apartment area (180–270°) are used.

**Figure 13.** Seasonal diurnal pattern of (a) the CO2 concentration (unit: ppm), and that of the CO2 flux (*FC*; unit: μmol m−2 s−1) during (b) all days, (c) working days, and (d) non-working days. Figures show the median, interquartile (box), 5th and 95th percentiles (whisker), and mean values (black dot). Only data from the apartment area (180–270°) are used.

**Figure 14.** (a) Vehicular traffic counts (vehicles per 30-min interval), (b) relationship between the CO2 flux (*FC*; unit: μmol m−2 s−1) and traffic, and (c) the temperature response of nocturnal *FC* (00:00–05:00) in bins of 50 data points. The error bars in (b) indicate standard error, and the shaded area in (c) indicates the interquartile range.

**Table 1.** Monthly mean air temperature (*Tair*; unit: °C), accumulated precipitation (unit: mm), and solar duration, compared to the 30-yr (1981–2010) average climatological value.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Season | Spring | | | Summer | | |
| Month | **2015–3** | **4** | **5** | **6** | **7** | **8** |
| *Tair* (oC) | 6.3  (+0.6) | 13.3  (+0.8) | 18.9  (+1.1) | 23.6  (+1.4) | 25.8  (+0.9) | 26.3  (+0.6) |
| Precipitation (mm) | 9.6  (–37.6) | 80.5  (+16.0) | 28.9  (–77.0) | 99.0  (–34.2) | 226.0  (–168.7) | 72.9  (–291.3) |
| Solar Duration (hr) | 270.8  (+81.8) | 216.0  (+11.0) | 290.4  (+77.4) | 258.1  (+76.1) | 176.1  (+56.1) | 207.0  (+54.5) |
| Season | **Autumn** | | | **Winter** | | |
| Month | **9** | **10** | **11** | **12** | **2016–1** | **2** |
| *Tair* (oC) | 22.4  (+1.2) | 15.5  (+0.7) | 8.9  (+1.7) | 1.6  (+1.2) | –3.2  (–0.8) | 0.2  (–0.2) |
| Precipitation (mm) | 26.0  (–143.3) | 81.5  (+29.7) | 104.6  (+52.1) | 29.1  (+7.6) | 1.0  (–19.8) | 47.6  (+22.6) |
| Solar Duration (hr) | 262.1  (+85.9) | 239.7  (+40.9) | 109.0  (–44.2) | 177.8  (+25.2) | 196.1  (+35.8) | 195.2  (+31.9) |

**Table 2.** First four moments of random flux error (*ε*) for *QH*, *QE*, and *FC*, and the linear relationship (Figs. 6d–f) between random flux error CO2 (*σ*(*ε*)) and the magnitude of the measured flux (). Only data from the south direction (135–315°) are used.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Season** | ***n*** |  |  | ***σ*(*ε*)** | ***σ*(*ε*)/** | **Skew** | **Kurt** | **Scaling at** |
| ***QH*** | **Total** | **882** | **59.7** | **0.9** | **16.4** | **0.28** | 0.3 | 5.8 | *σ*(*ε*) = 15.16 + 0.11×*QH*  *r*2 = 0.84 |
| Spring | 256 | 91.9 | 1.0 | 20.2 | 0.22 |
| Summer | 227 | 45.6 | –0.2 | 14.4 | 0.32 |
| Autumn | 269 | 46.2 | 1.9 | 12.8 | 0.28 |
| Winter | 130 | 48.7 | 1.0 | 15.9 | 0.33 |
| ***QE*** | **Total** | **838** | **21.9** | **1.4** | **18.2** | **0.83** | 0.8 | 7.4 | *σ*(*ε*) = 8.80 + 0.31×*QE*  *r*2 = 0.92 |
| Spring | 239 | 25.0 | 1.2 | 18.9 | 0.76 |
| Summer | 223 | 30.3 | 1.7 | 23.7 | 0.78 |
| Autumn | 251 | 18.7 | 1.7 | 16.0 | 0.86 |
| Winter | 125 | 7.6 | 0.7 | 5.4 | 0.71 |
| ***FC*** | **Total** | **928** | **7.9** | **0.02** | **6.3** | **0.80** | –0.2 | 4.4 | *σ*(*ε*) = 3.97 + 0.24×*FC*  *r*2 = 0.69 |
| Spring | 270 | 8.7 | 0.3 | 6.7 | 0.77 |
| Summer | 246 | 7.0 | 0.04 | 5.8 | 0.83 |
| Autumn | 267 | 7.0 | 0.2 | 6.4 | 0.91 |
| Winter | 145 | 9.9 | –0.8 | 6.5 | 0.66 |

**Table 3.** Daily (24-h), daytime (*Q\** > 0 W m−2), and night-time mean observed energy fluxes (unit: W m−2), which are down/upward short/longwave radiation (*K↓*, *K↑*, *L↓*, *L↑*), net radiation (*Q\**), sensible heat flux (*QH*), latent heat flux (*QE*), and the residual, with standard deviation values for each season. Only data observed from apartment areas (180–270o) are used.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | | **Spring** | **Summer** | **Autumn** | **Winter** |
| ***K*↓** | **All-day** | 333.0 ± 323.8 | 283.5 ± 293.0 | 215.1 ± 246.2 | 203.2 ± 207.6 |
| **Daytime** | 508.7 ± 274.1 | 434.7 ± 261.5 | 379.0 ± 217.9 | 335.1 ± 203.2 |
| **Night-time** | 13.7 ± 28.6 | 8.6 ± 19.8 | 8.4 ± 22.4 | 10.6 ± 24.3 |
| ***K*↑** | **All-day** | -62.6 ± 59.8 | -51.4 ± 52.6 | -39.5 ± 44.8 | -39.6 ± 40.2 |
| **Daytime** | -95.3 ± 50.2 | -78.6 ± 46.9 | -69.2 ± 39.8 | -65.0 ± 33.4 |
| **Night-time** | -3.3 ± 6.2 | -2.0 ± 4.1 | -2.1 ± 5.1 | -2.6 ± 5.7 |
| ***L*↓** | **All-day** | 314.6 ± 49.8 | 406.4 ± 29.2 | 336.6 ± 38.6 | 250.9 ± 39.6 |
| **Daytime** | 319.8 ± 45.9 | 407.3 ± 29.2 | 337.8 ± 41.1 | 250.2 ± 38.1 |
| **Night-time** | 305.1 ± 55.1 | 404.9 ± 29.2 | 334.9 ± 35.3 | 251.9 ± 41.8 |
| ***L*↑** | **All-day** | -407.3 ± 53.1 | -472.1 ± 31.6 | -406.6 ± 44.0 | -325.4 ± 23.2 |
| **Daytime** | -426.0 ± 49.5 | -486.7 ± 28.4 | -421.8 ± 46.3 | -333.6 ± 21.4 |
| **Night-time** | -373.4 ± 41.5 | -445.7 ± 16.1 | -387.5 ± 31.9 | -313.5 ± 20.5 |
| ***Q\**** | **All-day** | 177.6 ± 234.4 | 166.4 ± 212.1 | 105.5 ± 176.8 | 89.1 ± 148.9 |
| **Daytime** | 307.2 ± 193.2 | 276.7 ± 187.5 | 225.9 ± 150.7 | 186.8 ± 115.4 |
| **Night-time** | -57.9 ± 31.3 | -34.3 ± 21.3 | -46.2 ± 27.4 | -53.6 ± 28.4 |
| ***QH*** | **All-day** | 103.8 ± 97.3 | 75.1 ± 79.9 | 50.9 ± 67.4 | 59.3 ± 65.9 |
| **Daytime** | 150.1 ± 90.2 | 109.4 ± 79.1 | 89.6 ± 66.2 | 91.0 ± 63.7 |
| **Night-time** | 19.7 ± 30.4 | 12.7 ± 23.5 | 2.0 ± 21.8 | 12.9 ± 33.7 |
| ***QE*** | **All-day** | 27.5 ± 30.4 | 43.8 ± 45.7 | 21.4 ± 26.8 | 8.5 ± 10.6 |
| **Daytime** | 37.6 ± 31.7 | 60.8 ± 46.7 | 32.7 ± 28.5 | 10.7 ± 8.5 |
| **Night-time** | 9.0 ± 15.8 | 12.8 ± 20.5 | 7.1 ± 15.5 | 4.7 ± 9.3 |
| ***Residual***  **(= *Q\**-*QH*-*QE*)** | **All-day** | 46.3 ± 146.5 | 47.5 ± 129.7 | 33.2 ± 111.5 | 21.4 ± 102.2 |
| **Daytime** | 119.5 ± 131.0 | 106.4 ± 124.6 | 103.5 ± 99.7 | 84.8 ± 78.0 |
| **Night-time** | -86.7 ± 43.4 | -59.8 ± 36.8 | -55.4 ± 38.4 | -71.3 ± 48.5 |

**Table 4.** Daily (24-h), daytime (*Q\** > 0 W m−2), and night-time mean CO2 flux (*FC*; unit: μmol m−2 s−1) and standard deviation values for all, working, and non-working days. Only data observed from apartment areas (180–270o) are used.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | | **Spring** | **Summer** | **Autumn** | **Winter** |
| ***All Days*** | **All-day** | 10.3 ± 7.4 | 7.5 ± 6.1 | 8.9 ± 6.5 | 10.9 ± 7.1 |
| **Daytime** | 11.3 ± 7.2 | 7.3 ± 6.3 | 10.4 ± 6.3 | 11.9 ± 7.2 |
| **Night-time** | 9.0 ± 7.5 | 7.8 ± 5.9 | 7.2 ± 6.4 | 10.0 ± 6.9 |
| ***Working Days*** | **All-day** | 11.1 ± 7.6 | 8.1 ± 6.4 | 9.8 ± 6.8 | 11.6 ± 7.3 |
| **Daytime** | 12.4 ± 7.5 | 8.0 ± 6.6 | 11.8 ± 6.3 | 12.8 ± 7.6 |
| **Night-time** | 9.5 ± 7.3 | 8.1 ± 6.0 | 7.7 ± 6.7 | 10.4 ± 6.9 |
| ***Non-Working Days*** | **All-day** | 8.4 ± 6.8 | 6.1 ± 5.3 | 7.1 ± 5.6 | 9.6 ± 6.5 |
| **Daytime** | 9.0 ± 6.0 | 5.6 ± 5.2 | 7.8 ± 5.4 | 10.1 ± 6.1 |
| **Night-time** | 7.5 ± 7.8 | 6.9 ± 5.4 | 6.4 ± 5.6 | 9.2 ± 6.8 |