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Radiation fluxes in a business district of Shanghai, China

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ABSTRACT

Radiative fluxes are key drivers of surface-atmosphere heat exchanges in cities. Here the first year-long (December 2012 – November 2013) measurements of the full radiation balance for a dense urban site in Shanghai are presented, collected with a net radiometer CNR4 mounted 80 m above ground. Clear sky incoming shortwave radiation ($K_{\downarrow}$) (median daytime maxima) ranges from 575 W m⁻² in winter to 875 W m⁻² in spring, with cloud cover reducing the daily maxima by about 160 W m⁻². The median incoming longwave radiation daytime maxima is 305 and 468 W m⁻² in winter and summer, respectively, with increases of 30 and 15 W m⁻² for cloudy conditions. The effect of air quality is evident: ‘haze’ conditions decrease hourly median $K_{\downarrow}$ by 11.3%. The midday (11:00 -13:00 LST) clear sky surface albedo (α) is 0.128, 0.141, 0.143 and 0.129 for winter, spring, summer and autumn, respectively. α varies with solar elevation and azimuth angle due to heterogeneity of the urban surface. In winter, shadows play an important role in decreasing α in the late afternoon. For the site, the bulk α is 0.14. The NARP/SUEWS land surface model reproduces the radiation components at this site well, a promising result for applications elsewhere. These observations help to fill the gap of long-term radiation measurements in East Asian and low-latitude cities quantifying the effects of season, cloud cover and air quality.

1. Introduction

Radiative fluxes (shortwave and longwave) are the key drivers of surface exchanges of heat. However, for most cities worldwide long-term measurements of these fluxes are lacking. Here the first year-long measurements of the full radiation balance for a dense urban site in Shanghai (China) are presented, along with an evaluation of a simple model for their prediction. Of particular interest are differences with season and cloud cover, as well as the effects of air quality.

Radiative exchanges are impacted by the material characteristics of the urban surface (Aida and Gotoh 1982), urban form (Aida 1982) and the urban atmosphere (Qian et al. 2006). The surface albedo ($\alpha = K_{\uparrow}/K_{\downarrow}$ - the ratio of the reflected to the incoming solar shortwave radiation flux) has received particular attention, given it is a critical parameter in the performance of numerical land surface models (e.g. Masson 2000; Offerle et al. 2003; Loridan et al. 2010; Zhao et al. 2014) and its modification provides potential for altering local scale urban climate. For example, it has been proposed that changing roof materials (higher albedo) could mitigate the urban heat island effect in summer (Akabari et al. 1997; 2012, Bretz and Akabari 1997; Mackey et al. 2012; Li et al. 2014; Raman et al. 2014).

The framework used in this paper is the surface radiation budget, which combines the incoming ($\downarrow$) and outgoing ($\uparrow$) shortwave (K) and longwave (L) radiation fluxes to give the net all-wave radiation (Q^*) available for convection and conduction:

$$Q^* = [K_{\downarrow} - K_{\uparrow}] + [L_{\downarrow} - L_{\uparrow}] \quad (1)$$

Components of the atmosphere absorb, reflect and scatter the incoming solar radiation resulting in a reduction of the shortwave radiation reaching the surface. Solar radiation is absorbed by gases (O₂, O₃, H₂O, CO₂, CH₄, N₂O; Oke 1987) but also affected by high concentrations of atmospheric aerosols causing solar dimming (reduced atmospheric transmissivity and visibility) which significantly influences the receipt of solar radiation at the surface (Qian et al. 2006; Wang et al. 2012a; Wild 2012; Ding et al. 2013; Jiang et al. 2013; Nie et al. 2014). Incoming longwave radiation flux ($L_{\downarrow}$) also is influenced by cloud cover, cloud type, greenhouse gases and aerosols (Wang et al. 2013). In land surface models it is more difficult to estimate $L_{\downarrow}$ than $K_{\uparrow}$, due to the complex variability of cloud (cloud fraction, type and height) and atmospheric aerosols (Offerle et al. 2003). Tall buildings in cities trap radiation, thereby reducing both the effective albedo and the outgoing longwave radiation. This is a primary cause of the urban heat island effect (Oke 1982; Kondo et al. 2001).

Although direct measurements of the four components of the net all-wave radiation (Eq. 1) in urban areas are needed for a wide range of applications, there are still remarkably few long term measurements. Observations in cities are challenging because of complex urban surface-sensor-sun relations (Soux et al. 2004), the wide range of surface materials (Kotthaus et al. 2014) and their arrangements (e.g. Kotthaus and Grimmond 2014a, b), and logistical factors involved in siting equipment (Offerle

et al. 2003). In densely-built up cities with many tall buildings, the radiometer sensor height needs to be approximately 2.5 times that of the mean building height to measure representative local scale radiation fluxes (Offerle et al. 2003; Roberts 2010).

Despite these complexities and challenges a relatively small number of urban field studies of surface radiation exist. However, these have done much to enhance the understanding of the processes of the urban radiation budget (e.g. Grimmond et al. 1996; Christen and Vogt 2004; Moriwaki and Kanda 2004; Miao et al. 2012; Ward et al. 2013). Most urban measurements have been conducted over relatively low-rise buildings (suburban sites) with little analysis of temporal variations of the radiation fluxes and their controls (exceptions include Schmid et al. 1991; Kotthaus and Grimmond 2014a, b). Some studies include observations of radiation to help explain other processes. For example, the primary focus of Moriwaki and Kanda's (2004) was the turbulent heat flux partitioning (sensible and latent heat flux) in a residential area of Tokyo (mean building height: 7.3 m), with net radiation fluxes mentioned only as a driver of these processes. The mean diurnal patterns of the four components of radiation are reported only for two months (July, December).

In East Asia, ground-based radiation observations remain minimal. In China, for example, the focus has been on natural surfaces, such as the Tibet plateau and Gobi Desert (Wang et al. 2005; Wang et al. 2008; Li et al. 2010; Zhang et al. 2013). In Beijing, Miao et al. (2012) report measurements from the 325 m tower, but these have not yet been published in detail. To our knowledge, the radiation measurements presented here are the only full year study conducted in a central business district in China.

The objective of this study is to investigate temporal (diurnal and seasonal) variations of surface radiation fluxes in Shanghai based on one year of measurements in a neighbourhood with tall buildings. Particular attention is directed to the impact of the complex three-dimensional urban canyon structure, solar geometry and air quality on the solar radiation and surface albedo. The measurements are used to evaluate the radiation scheme in the land surface model SUEWS (Surface Urban Energy and Water balance Scheme). This research can inform the understanding of the energetic basis of urban atmospheric processes, such as the urban heat island (UHI) (e.g. albedo, net all wave radiation differences) for which there is extensive interest (e.g. Li et al. 2009; Wang et al. 2009; Li et al. 2015; Zhou et al. 2015; Sun et al. 2016). The data presented also have important utility for an array of applications, especially evaluations of land surface models, that can be used to contribute to the comfort, health and safety of city inhabitants and be instructive to urban planners and decision makers.

2. Methods

2.1 The site

Shanghai, the economic, financial, shipping and trade capital of China, has grown rapidly since 1970. Numerous tall buildings have been built to accommodate a population density of more than 15,000 people km⁻² (Shi and Cui 2012). Similar to large parts of central Shanghai, the study site is a densely built commercial and residential area, with pockets of educational and scientific institutions. The measurement site, located in Xujiahui (XJH, 31.19 °N, 121.43 °E), at the headquarters of the Shanghai Meteorological Service, has a long history of meteorological observations (Tan et al. 2015).

2.2 Observations

A net radiometer (CNR4, Kipp & Zonen) mounted 80 m above ground level (agl) (on top of a 25 m tower installed on a 55 m high building) is connected to a CR3000 datalogger (Campbell Scientific). The CNR4's four independent sensors (2 pyranometers and 2 pyrgeometers) measure the four components of net all wave radiation independently. The spectral response of the instrument is between 0.3 and 2.8 µm for shortwave radiation and between 4.5 and 42 µm for the far infrared or longwave radiation (Kipp and Zonen 2014). This model has been found to be more accurate than net radiometers (e.g. KZ NR lite) that do not measure the individual components (Blonquist et al. 2009; Wang et al. 2012b). Prior to installation the CNR4 sensor was calibrated by the manufacturer. The instrument is sampled every 1 minute, and 30 minute averages are recorded. The instrument has a response time (95%) of <18 s. Quality control processing includes forcing nocturnal shortwave radiation to 0 W m⁻² (Michel et al. 2008). For the year-long study period, after quality control, 86.0 % (N= 15071) of the 30 min periods are available. Losses of data are due to power failure, instrument malfunction or maintenance for short periods (e.g., 11 - 17 December 2012, 8 - 16 March 2013, Table 1). During rain events, water deposition on the sensor window or domes will obstruct the far infrared radiation, may increase measurement errors. However, these errors are likely small as the signal will be close to zero (Kipp and Zonen 2014).

The data analysed are for the year 1 December 2012 to 30 November 2013. All data referred to are local time and time

ending; 11:00 refers to data collected from 10:30:01 to 11:00. Daylight savings time is not used in Shanghai. The four seasons of a year are defined based on the commonly used classification in China: Winter (December – February; DJF), Spring (March – May; MAM), Summer (June – August; JJA) and Autumn (September – November; SON).

Manually observed cloud cover and cloud type were taken at the XJH Observatory three times per day (8:00, 14:00, 20:00 LST) until October 2013. Based on observed daytime cloud cover data (8:00, 14:00 LST), hourly rainfall data, the daily sky conditions are classified into clear, cloudy, overcast and rainy (Table 1). That is: when both the cloud cover at 8:00 and 14:00 LST are less than 20%, or the diurnal curve of $K_{\downarrow}$ is very smooth, the day is defined as a clear day; when the daytime cloud cover is between 30% and 80%, the day is defined as a cloudy day; when the daytime cloud cover is larger than 80%, the day is defines as a overcast day; when it rains in any hour within 24 hours a day, the day is defined as a rainy day. The occurrence of weather phenomena, such as the time of rain, snow, fog, dew, and haze, were also recorded. Precipitation data are obtained from the automated meteorological station (AWS, Vaisala MILOS500) located 60 m from the tower site. Particulate matter (PM) of 2.5 μm or smaller size are measured at around 50 m agl (on top of a building, about 50 m to the south from the CNR4 sensor) using a Thermo Fisher Scientific 5030 SHARP Monitor. The 1 min samples are averaged to provide hourly means. Following Xiao et al. (2011) and Zhang and Cao (2015), clear (cloudy) days are subdivided into haze or non-haze hours based on observed hourly visibility (Vaisala PWD22), relative humidity (RH) and PM_{2.5} concentration. That is: when the hourly visibility for clear (cloudy) days is larger than 10 km and PM_{2.5} is less than 35 $\mu\text{g m}^{-3}$, the hours are defined as clear (cloudy) none haze; when the hourly visibility for clear (cloudy) days is smaller than 10 km and relative humidity is less than 90% and PM_{2.5} is larger than 35 $\mu\text{g m}^{-3}$, the hours are defined as clear (cloudy) haze. The definition and data availability for all the sky conditions are also summarized in Table 1.

Tall buildings have a complex influence on the radiation budget of an urban environment. To document the urban morphology and sky view factors around the site, a Nikon D610 digital camera fitted with a fisheye hemispheric lens (Sigma 8 mm f3.5) was used to take onsite photographs that produce a hemispheric projection of the radiating environment onto a circular image. The manufacturer specified field of view (FOV) for the lens is 180° (Sigma 2013). The response time of the camera is milliseconds. Photographs were taken near the foot of the tower (i.e. at 55 m agl). This photographic method has been used widely to estimate sky view factors (Steyn et al. 1986; Grimmond et al. 2001; Chen et al. 2010).

Table 1. Data availability for different cloud cover (CC) conditions by month. Day are classified as clear or cloudy using manual the cloud observations at 08:00 and 14:00 LST taken at the site. Clear days are subdivided into haze or non-haze hours based on hourly visibility and humidity data.

Class (units)	Definition	Frequency											
		Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
a) Radiation data available (%)	Max: 48 per day * n days per month	57	82	90	61	95	89	85	96	97	93	91	97
(b) Frequency of cloud conditions and definition (days)													
Clear days (71 days)	Daytime CC < 20% / diurnal curve of $K_{\downarrow}$ very smooth	7	8	4	9	10	6	2	4	6	1	2	12
Cloudy (156 days)	Daytime CC: 30% to 80%	6	8	4	6	13	9	10	24	16	15	17	12
Overcast (13 days)	Daytime CC > 80%	0	3	0	0	0	1	0	0	1	4	2	2
Rainy (123 days)	Rain or snow during 24 h	11	9	20	9	7	14	18	3	8	10	10	4
(c) Clear hours daytime (Total: 1549 h)													
Clear non haze (313 hours)	Hourly: visibility >10 km & PM _{2.5} < 35 $\mu\text{g m}^{-3}$	0	0	13	41	30	44	0	53	70	12	22	28
Clear haze (79 h)	Hourly: visibility <10 km & RH <90% & PM _{2.5} > 35 $\mu\text{g m}^{-3}$	96	100	65	86	120	99	46	3	19	6	22	134

2.3 Analysis methods

To determine the bulk atmospheric transmissivity (τ), the incoming solar radiation at the surface is compared to the solar radiation flux received at the top of the Earth’s atmosphere ($K_{\downarrow, TOA}$):

$$\tau = K_i / K_{\downarrow, TOA} \tag{2}$$

The larger τ , the more transparent the atmosphere. To calculate the incoming solar radiation at TOA, a solar “constant” (S_0) of

1361 W m⁻² (Kopp and Lean 2011) was used with:

$$K_{\downarrow, TOA} = S_0 \left(\frac{r_0}{r} \right)^2 \sin h \quad (3)$$

The Earth-Sun distance (r) changes over the course of the Earth's annual elliptical orbit around the Sun relative to mean Earth-Sun distance (r_0). Here r/r_0 is calculated (Eva and Lambin 1998):

$$r/r_0 = 1 - 0.1672 * \cos(0.9856 * (D_{OY} - 4) * \pi / 180) \quad (4)$$

where D_{OY} is day of year. The solar elevation angle (h) is calculated from (Jacobson 2005):

$$\sin h = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \omega \quad (5)$$

where φ is the local latitude, δ is the declination of the Sun, ω is the hour angle.

3. Results and discussion

3.1 Characterisation of the shortwave radiation

All four components of the radiation budget were observed in this study (Fig. 1). The median daytime maxima of incoming shortwave radiation K_i for clear days ranged from 575 W m⁻² in winter to 875 W m⁻² in spring. As expected, this variation is much smaller than more northerly European cities, such as London (52° N), where daytime maxima range from about 200 to 1000 W m⁻² (Kotthaus and Grimmond, 2014a, b) and is similar to the closer site of Tokyo, Japan (35.57° N), where values range from 500 to 870 W m⁻² (Moriwaki and Kanda 2004). These latitudinal differences are primarily due to differences in the solar elevation angle. Daily maxima of the reflected shortwave radiation (K_r) reported here for Shanghai, range between 80 W m⁻² in winter and 150 W m⁻² in summer. The extremely low values of the incoming and reflected shortwave radiation documented in June 2013 (evident in Fig. 1) are a result of persistent rainfall.

When stratified by sky conditions (Fig. 2), it is evident that cloud cover fraction has a significant influence on the radiation fluxes. As overcast conditions without rain (Table 1) occurred on only 13 days, these are combined with cloudy conditions for the remaining analyses. Under cloudy conditions, the reduction (compared with clear conditions) of seasonal median midday (11:00-13:00 LST) K_i is 164 W m⁻² in winter, 128 W m⁻² in spring, 149 W m⁻² in summer, and 41 W m⁻² in autumn. The largest reductions occurred in February (370 W m⁻²) and June (352 W m⁻²) (not shown). In June, during the East Asian rainy season (commonly called the plum rain or Meiyu), precipitation occurs along a persistent stationary Meiyu front. During the 2013 Shanghai Meiyu period (7 to 30 June), when the cloud fraction is largest, the clouds (Fig. 3) were always *altostratus opacus*, *stratocumulus opacus*, *altocumulus opacus* or *fractonimbus* (*As op*, *Sc op*, *Ac op*, *Fn*). During February 2013, a continuous rainy period resulted in the second largest mean cloud cover fraction (Fig. 3).

On rainy days (Table 1), K_i decreases markedly during winter, spring and autumn, with seasonal median daytime peaks only 141 – 303 W m⁻². Compared with clear conditions, the reduction of the median daytime peaks is 435 W m⁻² in winter, 632 W m⁻² in spring, 575 W m⁻² in summer and 111 W m⁻² in autumn. The inter-quartile range (IQR) of the solar radiation under cloudy and mixed rainy conditions (Fig. 2), as expected, is much larger than under clear conditions.

The bulk transmissivity τ under different sky conditions is used to assess the influence of cloud, haze and rain on K_i (Fig. 4, 5). For clear conditions, the monthly midday median (11:00 - 13:00 LST) τ is between 0.6 - 0.7, and decreases steadily from winter to spring to summer to autumn (0.69, 0.68, 0.64 and 0.63). This seasonal trend may relate to increased absorption and reflection by more water vapour in the air in the summer and autumn (Fig. 1f shows large absolute humidity values at this site in summer and autumn) and/or different seasonal composition of aerosols (Fu 2009; He et al., 2012, Zhang and Cao 2015). Although τ decreases near sunrise and sunset due to increased solar path-length through the atmosphere, τ values are smaller near sunrise than sunset in most months. This may relate to the frequent presence of residual layers overnight (Peng et al. 2016) which become more dispersed by mixing later in the day. For cloudy conditions, the midday τ was 0.47, 0.59, 0.49 and 0.48 in winter, spring, summer and autumn, respectively. For rain or snow days, the monthly midday τ is much lower, 0.10 - 0.47.

The increasing emission of anthropogenic aerosols caused by the ever-growing population and human activities in Shanghai has resulted in the frequent occurrence of haze, especially during autumn and winter (Qian et al. 2015). Haze aerosols reflect, scatter and absorb the solar radiation resulting in a decrease of K_i reaching the surface. When clear days are stratified by the presence (or not) of haze, its effects on solar radiation can be assessed (Fig. 5). For the study period, τ is decreased by about 0.07 (11.3% of the hourly average 0.65) between those hours with and without haze.

In terms of seasonal patterns, under clear sky conditions the median τ increases steadily with solar elevation angle from 4°

to 60° (Fig. 5e); with solar elevation angles $> 60^\circ$, τ becomes constant (with values around 0.67). Under cloudy sky conditions, the variation of τ with solar elevation is similar, but with values of τ decreased by 0.12. For rainy conditions, there is no obvious variation of τ with solar elevation, with values varying from 0.1 to 0.19. When clear sky days are stratified into those with and without haze (Table 1), when the solar elevation angle is below 60° τ is further attenuated by haze by 0.07 ($\sim 11.6\%$). However, when the solar elevation angle is larger than 60° , the impact of haze is less, with τ under haze conditions even slightly larger than when there is no haze. This may be a consequence of multiple scattering enhancing diffuse radiation receipt.

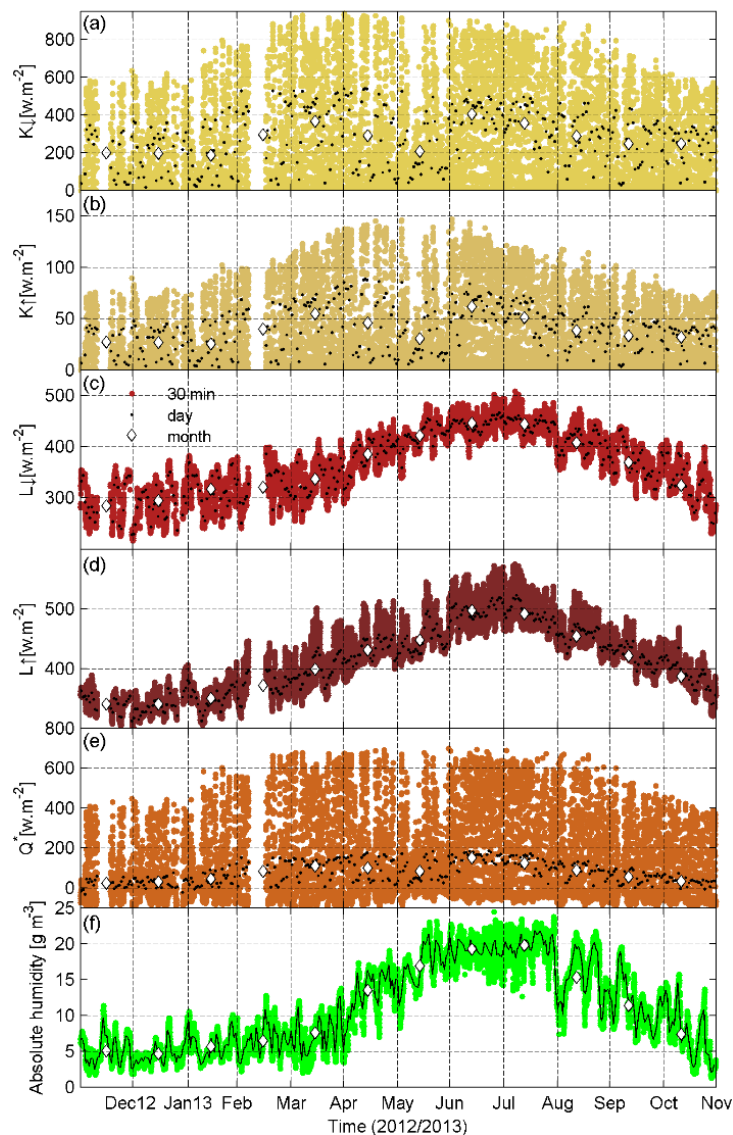


Figure 1. Observed 30 min fluxes (coloured dots) (a) incoming shortwave radiation ($K_{\downarrow}$), (b) outgoing shortwave radiation ($K_{\uparrow}$), (c) incoming longwave radiation ($L_{\downarrow}$), (d) outgoing longwave radiation ($L_{\uparrow}$), (e) net all-wave radiation (Q^*); (f) absolute humidity calculated using observed data at the automated weather station at XJH at 2 m above ground: hourly (dots), daily (solid line) in Shanghai (2012/2013) with monthly (white diamonds) and daily (black dots, shortwave radiation for sunlight hours) means.

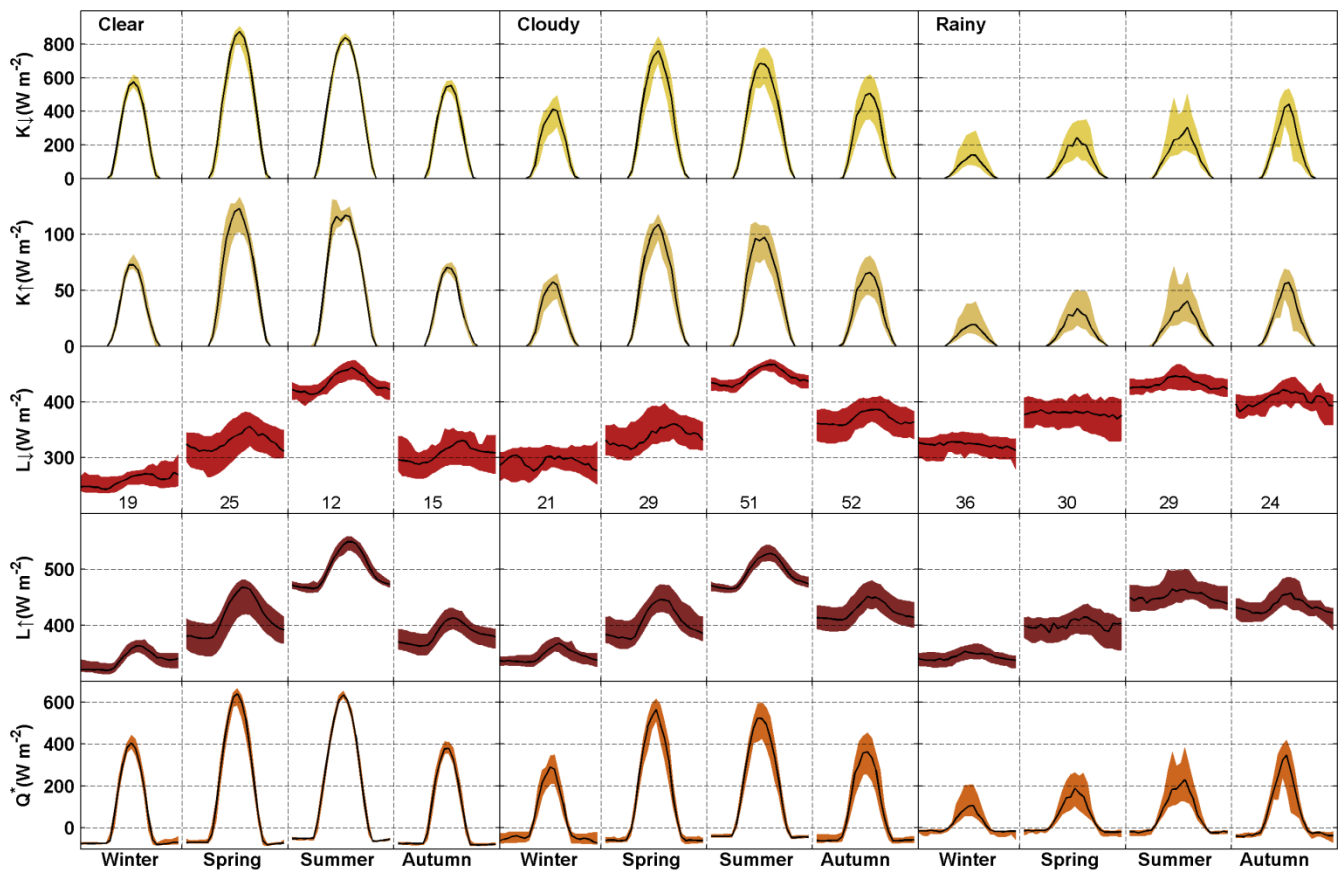


Figure 2. Seasonal median diurnal (line) radiation fluxes (rows) under clear, cloudy and rainy conditions (columns) with inter-quartile range (shaded). Number of days per season per sky condition is given in row 3.

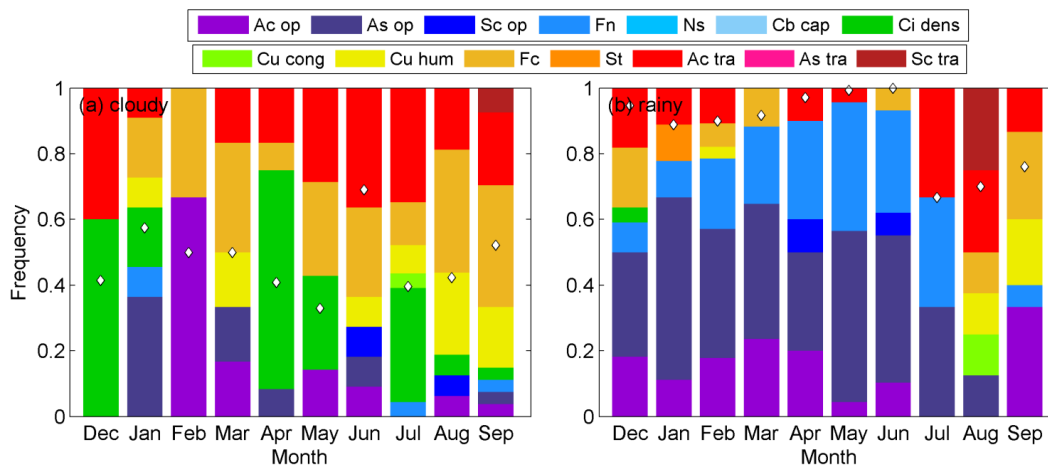


Figure 3. Frequency of 14 cloud types (see WMO 1975 for cloud classification and code definitions) at 08:00 LST at XJH by month for the study period (Dec 2012 – Sep 2013) under (a) cloudy and (b) rainy conditions. The mean cloud fraction by month (white diamonds) is also shown. In October 2013 manual cloud observations ceased at this site

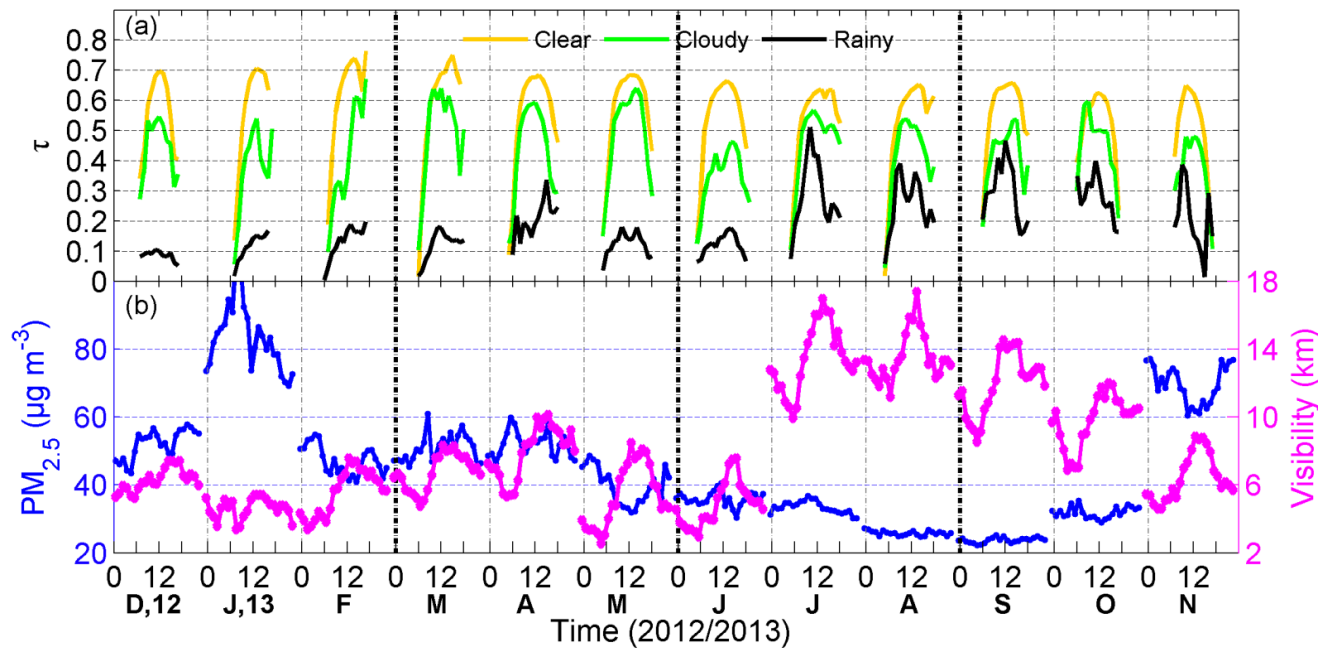


Figure 4. Median monthly diurnal transmissivity (τ) on (a) clear (haze and non-haze combined), cloudy and precipitation (rain or snow) days; (b) $PM_{2.5}$ concentration (observed 50 m from XJH) and visibility (observed at 2 m at XJH by a Vaisala PWD22).

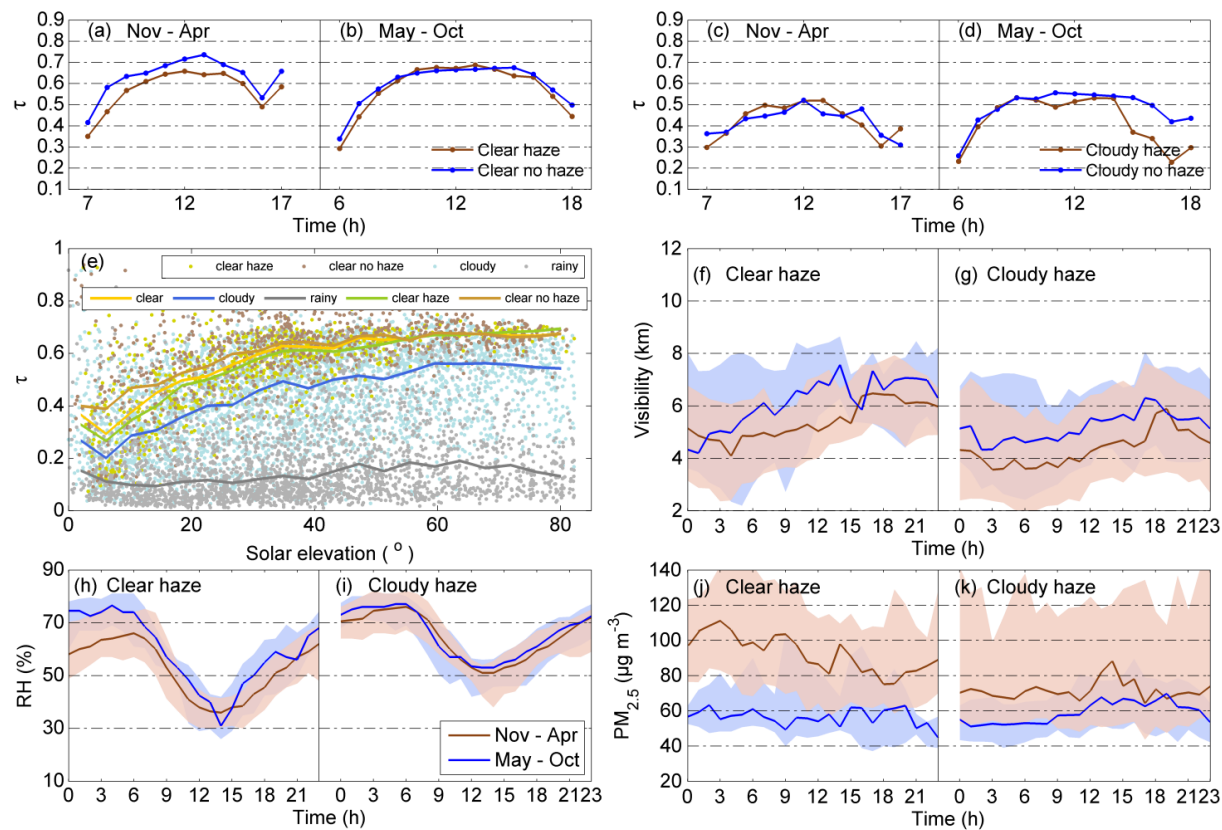


Figure 5. Median diurnal transmissivity (τ) under (a, b) clear ‘haze’ and ‘no haze’ conditions: (a) November to April and (b) May to October; (c, d) under cloudy ‘haze’ and ‘no haze’ conditions: (c) November to April and (d) May to October; (e) 30 min (dots) and median (lines, 4° bin midpoint plotted (i.e. 2 is for $0 - 4^\circ$)) τ as a function of solar elevation angle under clear skies (haze, no haze), cloudy and rainy conditions; (f, g) median (lines) and IQR (shading) diurnal visibility (observed at 2 m at XJH by a Vaisala PWD22) by time of year (Nov – Apr, brown; May – Oct, blue) during clear and cloudy haze conditions (visibility < 10 km); (h, i) same as (f, g) but for relative humidity (RH); (j, k) same as (f, g) but for $PM_{2.5}$.

The monthly median $PM_{2.5}$ concentrations (Fig. 4b) were higher from November to April than May to October. This is attributed to boundary layer dynamics and the effects of different large-scale synoptic systems affecting the Shanghai area in these two periods (Zhang et al. 2010). During the period of higher concentrations (November to April), the synoptic situation is

generally less variable with northwesterly or northerly winds, which import PM_{2.5} into Shanghai. In contrast, during the less polluted period the main synoptic control is the subtropical high-pressure belt, with low pressure troughs and typhoon systems. These synoptic systems tend to be associated with relatively strong easterly or southeasterly winds, which can transport ‘clean air’ into coastal Shanghai from the sea and dilute the pollution generated in the city. The diurnal variation of τ for ‘haze’ and ‘no haze conditions’ (Table 1) for these two periods are shown in Fig. 5a-e. Under clear sky conditions in winter τ was consistently smaller (by about 0.09) for haze conditions (Fig. 5a). This represents a 12.9% decrease in τ and daytime shortwave radiation receipt. However, the difference is less (11.2%) during the summer (Fig. 5b). This is attributed to greater visibility (Fig. 5f, g) and much lower concentrations of PM_{2.5} (Fig. 5j, k). Moreover, the stronger convection of the atmosphere in summer results in greater dilution of near surface PM_{2.5}. Thus the measured near surface PM_{2.5} probably is not as representative of the total column PM_{2.5} in summer than in winter when stagnant weather and inversion layers occur more frequently (Zhang and Cao 2015). Under cloudy sky conditions, τ was even larger under haze conditions in winter (Fig. 5c), and consistently smaller in summer (Fig. 5d). As cloudy conditions have a wider range of cloud cover fraction (0.2-0.8), the haze influence may be affected by the cloud cover effect. The controls on atmospheric chemistry and ‘haze’ are more complex than just synoptic conditions and wind directions. Changes in temperature, moisture, radiation, stability, boundary layer depth and emissions (quantity, types) all will impact atmospheric chemistry with feedbacks to the radiative fluxes and hence τ . A more comprehensive explanation of the radiation forcing of haze conditions needs further detailed analysis of the chemical compositions of PM_{2.5} and the meteorological conditions.

3.2 Characterisation of the longwave radiation

Variations in incoming long-wave radiation ($L_{\downarrow}$) are primarily correlated with near surface air temperature, sky view factor, water vapour and the existence of middle or low level clouds (Flerchinger et al. 2009, Wang et al. 2013). Thus, the annual variation of the observed $L_{\downarrow}$ in Shanghai is very similar to that of the air temperature. The lowest monthly mean $L_{\downarrow}$ was observed in December 2012 and January 2013 (284, 294 W m⁻²), the two coldest months in the observation period. The highest monthly mean $L_{\downarrow}$ was observed in July and August (446, 444 W m⁻², respectively). At this site, the daily maxima of $L_{\downarrow}$ varied from 382 W m⁻² in winter to 509 W m⁻² in summer (Fig. 1). Diurnal patterns under clear sky conditions also are mostly governed by diurnal temperature variations.

In general, cloud cover enhances $L_{\downarrow}$ (Fig. 6). While the increase is smaller in spring (median diurnal: 2 – 19 W m⁻²) and summer (5 – 18 W m⁻²) than that in winter (6 – 56 W m⁻²) and autumn (49 – 71 W m⁻²). This variability is a response to the water content (Fig. 1f) and cloud cover of the atmosphere. The average increases under cloudy relative to clear conditions for the four seasons (winter, spring, summer, autumn) are about 30, 18, 15, 60 W m⁻², with increases greater again for rainy conditions, except for summer (53, 50, 5, 88 W m⁻² for the four seasons, respectively). This effect of rainy days is undoubtedly due to the more extensive cloud cover. The reductions of $L_{\downarrow}$ under rainy conditions by about 1-21 W m⁻² (diurnal median) from 10:00 LST to 21:00 LST in summer, may be caused by lower air temperatures on these days than under clear conditions. For example, June was cool with 18 rainy days and only 2 clear days, compared with the warmer and drier July and August (3, 8 rainy days; 4, 6 clear days, respectively).

Outgoing long-wave radiation ($L_{\uparrow}$) is directly influenced by the urban surface temperature. Thus it depends on the amount of the total incoming radiation energy, $Q_{\downarrow} = K_{\downarrow} + L_{\downarrow}$, the conduction and convection heat exchange processes at the surface, and the nature of the urban surface facets. The annual pattern of $L_{\uparrow}$ is even more similar to the annual pattern of near surface air temperature than $L_{\downarrow}$ (Fig. 1 cf. Fig. 3 in Ao et al. 2016).

As net all-wave radiation Q^* (Fig. 1, Fig. 2) combines the four radiative components, it responds to the sun’s elevation, surface characteristics and cloud cover. Median daily maximum values in Shanghai under clear conditions range from 400 W m⁻² in winter to 640 W m⁻² in spring. The monthly average Q^* remains positive throughout the year. However, during winter months radiative cooling exceeds the gain from solar input for individual days. Hence daily average Q^* can become negative. The median diurnal pattern of Q^* under different sky conditions was, as expected, similar to $K_{\downarrow}$.

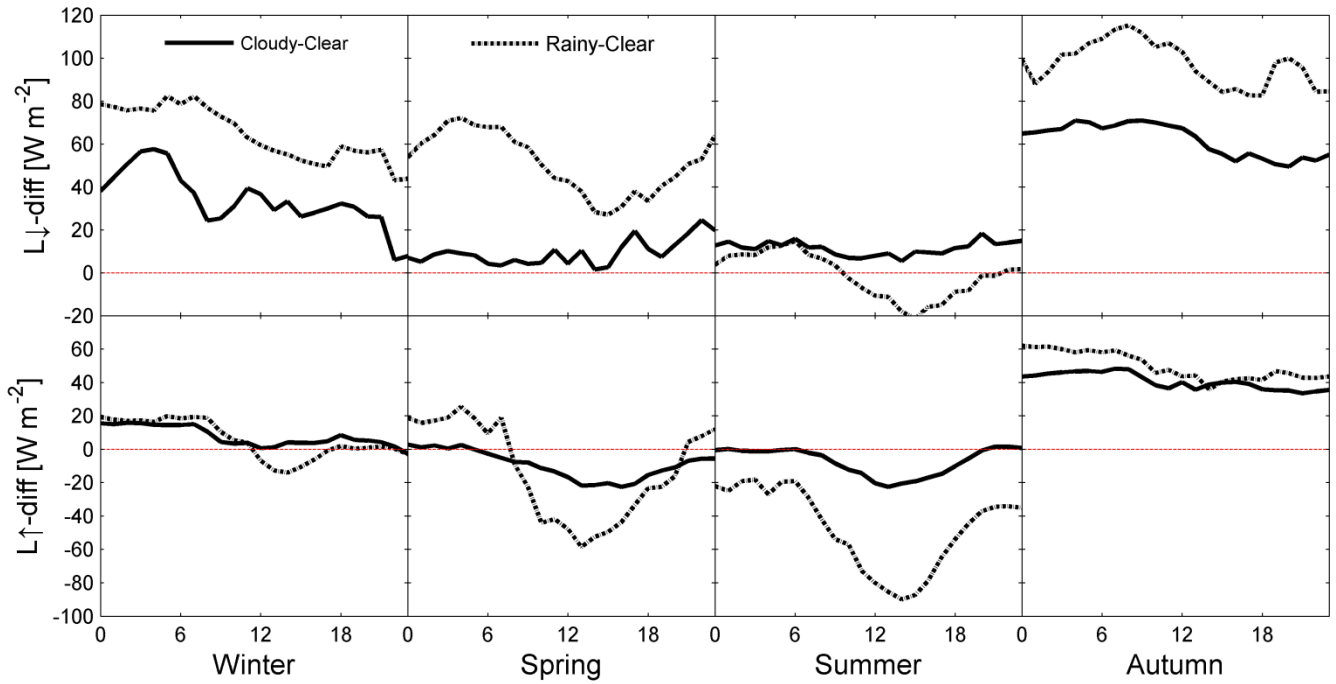


Figure 6. Seasonal differences between the diurnal medians of cloudy/rainy and clear conditions for (a) $L_{\downarrow}$ and (b) $L_{\uparrow}$.

3.3 Surface albedo

Surface albedo (α), a key parameter in numerical prediction models, influences radiative exchanges between the surface and the atmosphere (Liu et al. 2008). Fig. 7 shows the median diurnal variations of surface albedo by season under different sky conditions when both K_d and K_f were $>2 \text{ W m}^{-2}$. Overall, the albedo has the typical diurnal U shape pattern observed at other urban sites (e.g. Aida 1982). When the sun elevation is low ($<8^\circ$) near sunrise and sunset, the surface albedo is >0.2 , while the values are lower and almost constant during the middle of the day. In the morning the albedo is usually larger than in the afternoon, with an obvious increase around 08:00 or 09:00 LST from May to August. This is evident under both clear and cloudy conditions in summer (Fig. 7). This may be due to the effect of shadows in the afternoon (further discussed below) as documented elsewhere for other urban areas with deep canyons (Minnis et al. 1997; Grimmond et al. 2004; Zhang et al. 2013; Kotthaus and Grimmond 2014b).

The surface albedos under clear conditions near noon (11:00–13:00 LST) are 0.128, 0.141, 0.143 and 0.129 for winter, spring, summer and autumn, respectively. The surface albedo under clear or cloudy conditions increases with solar elevation (Fig. 8), while under rainy conditions the albedo remains more constant through the year (0.146, 0.142, 0.137, 0.132 for winter, spring, summer, autumn, respectively). The relation between surface albedo and solar elevation under different sky conditions provides corroboration for remote sensing results (e.g. Lucht et al. 2000; Schaepman-Strub et al. 2006). Under rainy conditions the surface itself will be wet so there is an expected decrease in surface albedo. However, again it should be noted that the sensor (notably the incoming shortwave sensor) may be impacted by water droplets for some of the time. Albedo increases with cloud fraction (at 14:00 LST; the time in the middle of the day with direct cloud observations) (Fig. 9), notably, when cloud fraction is $>40\%$, below that the effect of solar elevation angle dominates (Fig. 9). The combined influence of solar geometry and sky conditions on the surface albedo is assessed by comparing the median α with solar elevation angle stratified by sky conditions (clear, cloudy and rainy) and solar azimuth angle (easterly E and westerly W, Fig. 9c). Higher surface reflectances at lower solar elevation angles can be caused by increased specular reflectance by urban materials such as glass and metal (Kotthaus and Grimmond 2014b). This, however, is not particularly evident here. The surface albedo has a sharp decrease when solar elevation angle rises from 0 to about 8° under all sky conditions. The surface α for solar elevation angles $<44^\circ$ decreases from rainy to cloudy to clear conditions, whereas for solar elevation angles $>44^\circ$ the inverse occurs, albeit the differences between conditions are smaller. Under clear conditions, α is strongly influenced by direct radiation reflection (assuming no shadows), while under rainy/cloudy conditions diffuse radiation dominates (Lucht et al. 2000). The surface α varies with solar azimuth angle (simplified here to East and West) in correspondence with surface heterogeneity, both under clear and overcast conditions. This indicates that the urban canyon absorbs both direct and diffuse radiation. The surface appears less-reflective (darker) when solar rays come from the West as the shadows of many tall buildings (e.g. the Sports Hotel) are within a radius of

20-30 m of the tower in this direction. This results in trapping of shortwave radiation. Under rainy conditions the difference in α is smaller between East and West, and becomes constant with solar elevation angles $> 40^\circ$. The dominance of diffuse radiation almost removes dependence on solar geometry.

Thus the larger range of α with solar elevation under clear conditions is attributed to building shadows increasing the spatial variability of surface conditions in the source area of the measurements. Analysis of fish-eye photographs taken at the foot of the tower show a significant surface element is the Sports Hotel located to the southwest (Fig. 9d, indicated by the green rectangle). The mean albedo (binned 1° elevation $\times 1^\circ$ azimuth, Fig. 9e as a function of sun position) demonstrates the significantly lower albedo (Fig. 9e, indicated by the blue rectangle) in the late afternoon in winter seems to be caused by shadows from the Sports Hotel.

Despite significant variation of α with sky conditions and sun-surface geometry, a bulk surface albedo can be calculated to represent the overall characteristics of this site. The median all-sky value (solar elevation $> 20^\circ$) α is 0.14 (IQR= 0.02). This is similar to values for other central business districts (for example in London as reported in Kotthaus and Grimmond 2014a, b).

Considering both transmissivity and albedo, the median τ increases from 0.15 to 0.45 with solar azimuth angle (65 to 100°) in the morning (Fig. 10) and is asymmetric around noon. However, the afternoon slope decrease is flatter than in the morning. When stratified by seasons, the obvious increase of τ with azimuth angle between $235 - 255^\circ$ seems to be related to the greater sky view in this direction as no high buildings are present (fish-eye photo, Fig. 9d). The median surface α is more variable when the sun is in the east than in the west. Overall, the surface albedo is larger near sunrise than near sunset. The seasonal variation of surface albedo as a function of solar azimuth angle is small.

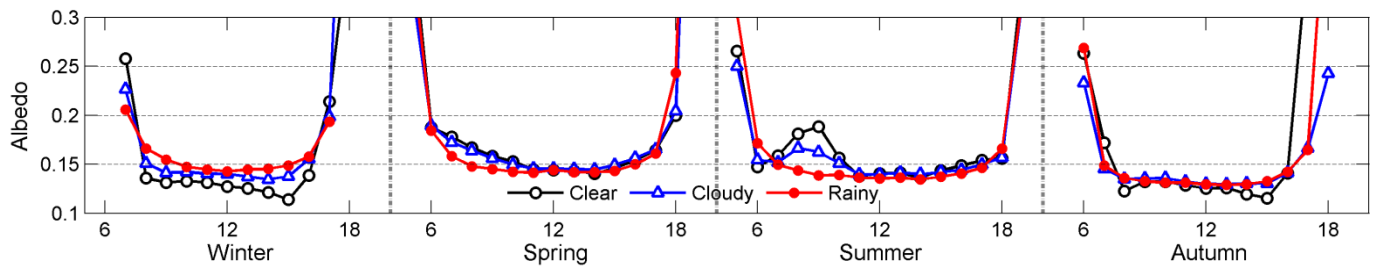


Figure 7. Median diurnal variations of surface albedo (α) under clear, cloudy and rainy conditions (Table 1). See Figure 2 (row 3) for number of each type of day in each season.

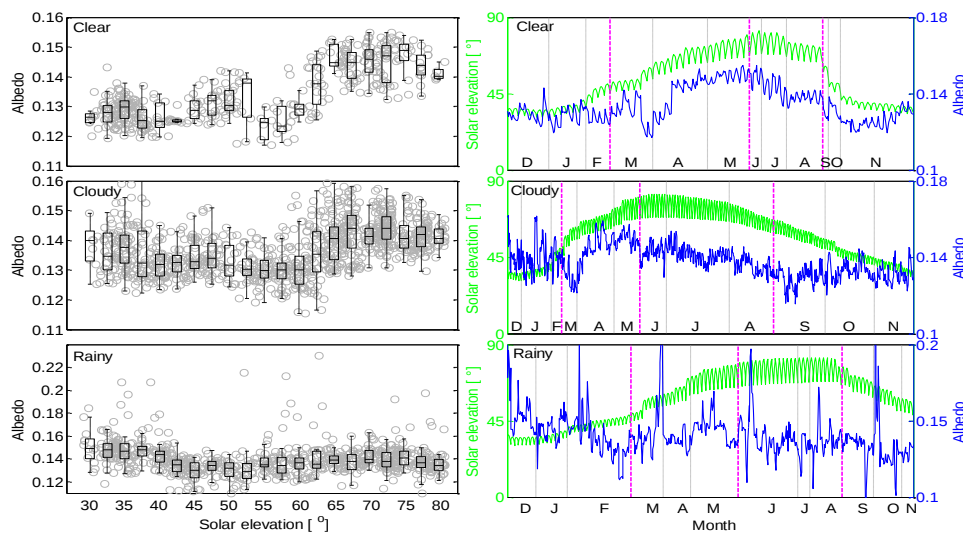


Figure 8. Variation of 30 min surface albedo (α) near midday (11:00-13:00 LST) with solar elevation angle (h) stratified by sky conditions (Table 1). (a) Box plots at 2.5° solar elevation intervals show median, interquartile range and 1.5 IQR whiskers. (b) time series with vertical lines to indicate the end of each month (pink the seasons) as the varying frequency of conditions cause the Time (x-) axis to be inconsistent between rows.

Figure 9. Variation of surface albedo (α) (a)

with cloud cover (manually observed at XJH) at 14:00 LST from December 2012 to September 2013: daily (point) median (solid line), mean (grey dotted line), inter-quartile range (black dotted line). Note only three values occur in the 10 % bin; (b,c) median as a function of solar elevation angle (b) under clear, cloudy and rainy conditions (Table 1); (c) sunny and rainy conditions stratified into E (sun in the East) and W (sun in the West). Solar elevation angle bins of 4° (0 is for 0 - 4°); (d) Fish-eye photograph taken at the foot of the measurement tower. Dotted lines indicate sun position (every 30 min) on the summer solstice (green), winter solstice (blue), vernal / autumnal equinox (pink/black) and 9 July 2014 when the photograph (16:30 LST) was taken. Green rectangle contains the Sports Hotel; (e) mean surface albedo (bins 1° solar elevation (radial) x 1° solar azimuth (angular) angle) as a function of sun position. Blue rectangle corresponds with impact of Sports Hotel.

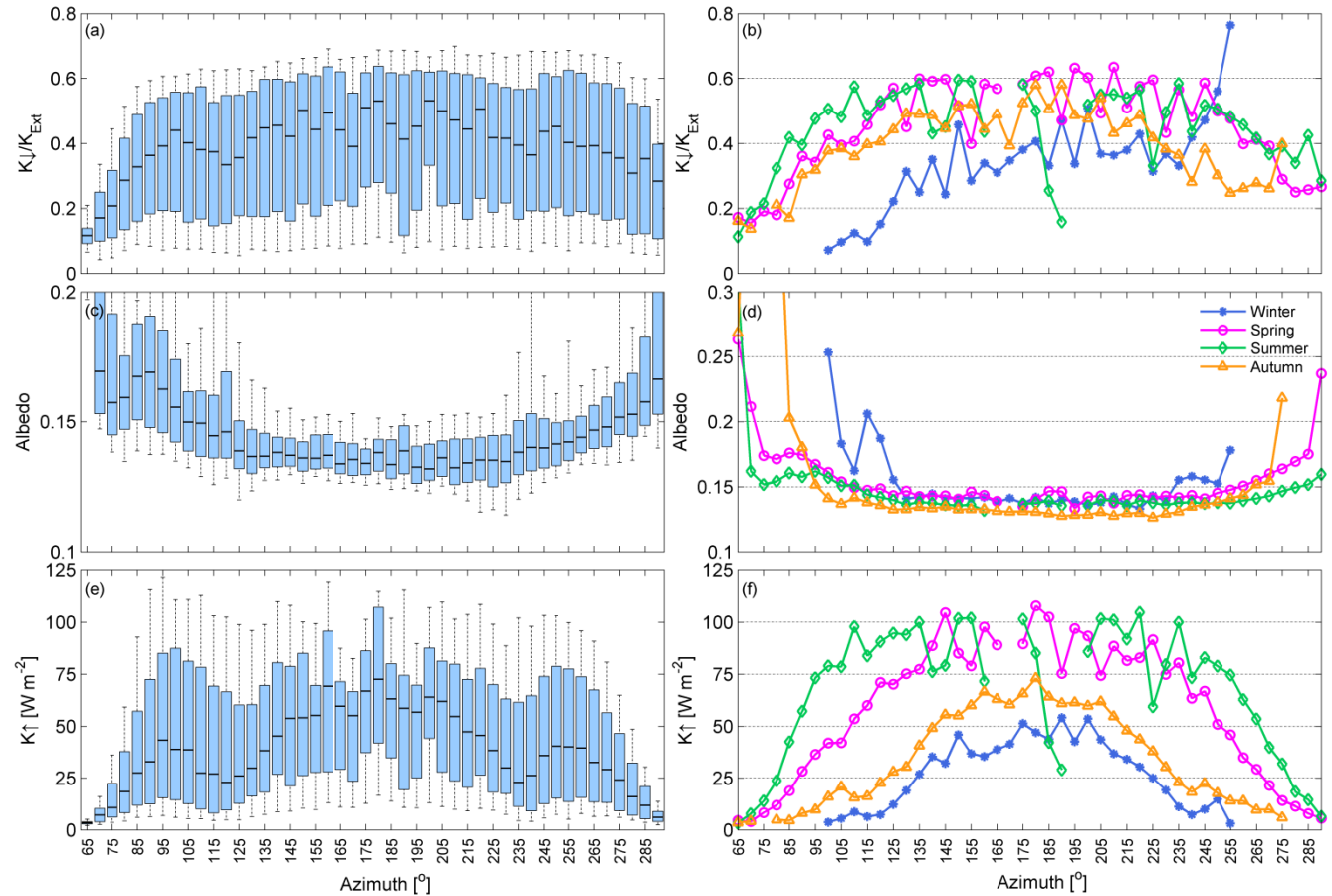
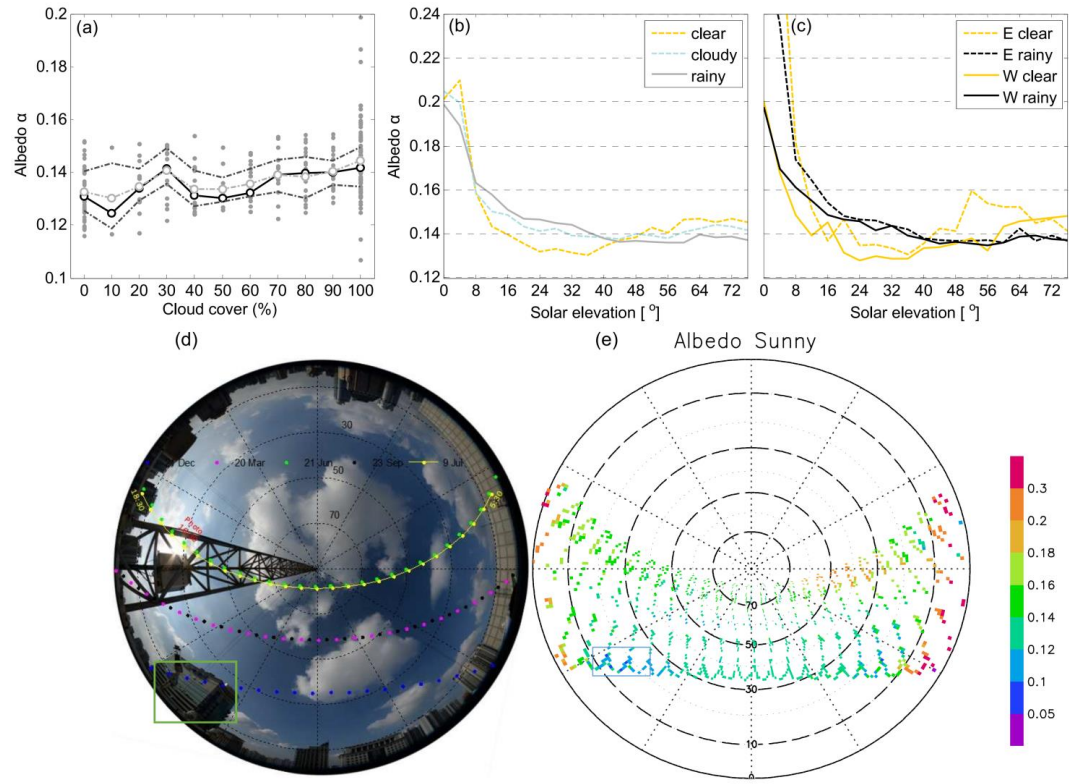


Figure 10. Median (a, b) transmissivity (c, d) albedo (e, f) outgoing shortwave radiation fluxes with solar azimuth angle. (a, c, e) for year with inter-quartile range and (10, 90 percentiles) whiskers (b, d, f) by season.

3.4 Evaluation of a radiation parameterization scheme

Often direct measurements of radiative fluxes are unavailable so urban land surface schemes are used. Here the Shanghai data are used to evaluate the **Net All-wave Radiation Parameterization** scheme - NARP (Offerle et al. 2003; Loridan et al. 2011) within the Surface Urban Energy and Water balance Scheme - SUEWS (Järvi et al. 2011; Ward et al. 2016, v2016a) using hourly data. The evaluation metrics used are the coefficient of determination (R^2), linear regression slope and intercept, root mean square error (RMSE), mean bias error (MBE) and mean absolute error (MAE):

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (M_i - O_i)^2}, \quad MBE = \frac{1}{N} \sum_{i=1}^N (M_i - O_i), \quad MAE = \frac{1}{N} |M_i - O_i| \quad (6)$$

where M_i are modelled values, O_i observed values and N is the number of data points. The metrics are calculated using hourly data ($N = 7365$) when no rainfall (hourly rainfall = 0 mm) was recorded.

The NARP local scale (10^2 - 10^4 m) net all-wave radiation (Q^*) simulations require commonly measured meteorological variables and surface cover information. The outgoing short-wave (Offerle et al. 2003) is determined using forcing provided by the downward short-wave radiation flux ($K_{\downarrow}$):

$$K_{\uparrow} = \sum (f_i \alpha_i) K_{\downarrow} \quad (7)$$

where α_i is the surface albedo for each surface type (i) which has fractional plan area (f_i). The incoming longwave radiation ($L_{\downarrow}$) is modelled using (Offerle et al. 2003):

$$L_{\downarrow} = \varepsilon_{sky} \sigma T_{sky}^4 \quad (8)$$

where σ is the Stefan-Boltzman's constant ($W m^{-2} K^{-4}$), T_{sky} is the bulk atmospheric temperature estimated as the measured air temperature (T_a) near the surface, the atmospheric emissivity ε_{sky} is corrected from Prata's (1996) clear-sky ε_{clear} to account for cloud effects:

$$\varepsilon_{clear} = 1 - (1 + w) \exp[-(1.2 + 3.0w)^{0.5}]; \quad w = 46.5 e_a / T_a; \quad \varepsilon_{sky} = \varepsilon_{clear} + (1 - \varepsilon_{clear}) F_{CLD} \quad (9)$$

where w is the precipitable water content ($g cm^{-2}$) approximated by atmospheric vapour pressure (e_a) and T_a , F_{CLD} represents the cloud cover fraction. In NARP, F_{CLD} can be estimated from measured $K_{\downarrow}$ or estimated as a function of relative humidity (RH) and T_a (Loridan et al. 2011). The latter was used here:

$$F_{CLD}(RH, T_a) = 0.185 [e^{(0.015 + 1.9 \times 10^{-4} T_a) \times RH} - 1] \quad (10)$$

Finally, yielding this parameterization for $L_{\downarrow}$:

$$L_{\downarrow}(e_a, T_a, RH) = \{\varepsilon_{clear}(e_a, T_a) + [1 - \varepsilon_{clear}(e_a, T_a)] \times F_{CLD}(RH, T_a)\} \times \sigma T_a^4 \quad (11)$$

The surface outgoing longwave radiation ($L_{\uparrow}$) is estimated as (Offerle et al. 2003):

$$L_{\uparrow} = \varepsilon_0 \sigma T_a^4 + 0.08 K_{\downarrow} (1 - (\sum f_i \alpha_i)) + (1 - (\sum f_i \varepsilon_i)) L_{\downarrow} \quad (12)$$

where ε_i is the surface emissivities for the component surface types.

The 100 % field of view (FOV) (Schmid et al. 1991) for the radiometer used for the measurements has a radius of 80 m. The plan area surface characteristics were determined for this area and for 500 m around the site using the methods described in Ao et al. (2016). The latter area contributes to the eddy covariance (EC) flux measurements. These fractions were used with the other parameters (Table 2) for the model runs (1 December 2012- 30 November 2013).

NARP/SUEWS successfully reproduces the diurnal cycle of fluxes (Fig. 11) with similar results for the two sets of plan area fractions (radiometer FOV (80 m), EC source area (500 m)). The seasonal mean daily maxima of $K_{\uparrow}$ are underestimated in spring and summer (i.e. negative MBE), whilst overestimated in winter and autumn (i.e. positive MBE) but there are high R^2 values (0.98-0.99.) and small RMSE values (2.6 (winter) to 5.8 $W m^{-2}$ (summer)). Typically, the greatest deviation from 1:1 relations occurs in the early morning and late afternoon hours.

The diurnal cycle of downward longwave radiation ($L_{\downarrow}$) in spring and summer is reproduced relatively well by the model. The larger observed and simulated values occur in the afternoon. However, the amplitude of the diurnal variation was underestimated for all seasons. This is mainly because that the range of modelled F_{CLD} based on eq. 10 is too narrow (Ward et al. 2016). The RMSE for $L_{\downarrow}$ varies from 19.3 $W m^{-2}$ (summer) to 29.3 $W m^{-2}$ (winter). There is a positive bias for all seasons except winter. This change in positive to negative bias in winter was also documented in Baltimore and Lodz (Loridan et al. 2011). This may be due to the formulation of eq. 10 for F_{CLD} being for a relatively narrow annual range of T_a observed in London, or a consequence of the form of the function (Ward et al. 2016). Lower (higher) bias may occur in colder (warmer) temperatures (Loridan et al. 2011).

Although the mean diurnal variation of outgoing longwave radiation $L_{\uparrow}$ is well simulated for all seasons, the mean daily maximum is overestimated in each season. The R^2 varies from 0.84 to 0.97, RMSE varies from 7.8 to 10 $W m^{-2}$, MBE varies from

1.7 to 4.1 W m⁻², and mean absolute error (MAE) varies from 5.6 to 7.1 W m⁻².

The net result is that SUEWS/NARP underestimates the mean daytime Q* in all seasons and overestimates night-time Q*. The overall RMSE for Q* is 26 – 27.8 W m⁻² and MAE 21 – 24.5 W m⁻² for all seasons. The MBE for Q* is negative in winter (-10.7 W m⁻²), and positive in spring (1.8 W m⁻²), summer (8.9 W m⁻²) and autumn (3.2 W m⁻²). The overall performance of NARP at the XJH site is comparable with other more northerly and non-Asian city sites (e.g. Loridan et al. 2011).

Table 2. SUEWS model input parameters by surface type (*i*): minimum ($\alpha_{i\min}$), maximum ($\alpha_{i\max}$) albedo, emissivity (ϵ_i), and fraction of the *ith* surface (f_i). Sources of data are: ^a Oke (1987); ^b Järvi et al. (2014); ^c Ao et al. (2016). The surface fractions are for circle of 500 m radius (about 80% eddy covariance flux source area) and of 80 m radius (100% radiation sensor field of view).

	Paved	Building	Evergreen Tree/shrubs	Deciduous Tree/shrubs	Grass	Bare soil	Water
$\alpha_{i\min}$	0.12	0.18	0.1	0.12	0.18	0.21 ^a	0.1 ^a
$\alpha_{i\max}$	0.14	0.18	0.1 ^b	0.18 ^a	0.21 ^a	0.21 ^a	0.1 ^a
ϵ_i^p	0.95	0.91	0.98	0.98	0.93	0.93	0.95
$f_{i-500\text{m}}^c$	0.62	0.23	0.03	0.01	0.1	0	0.01
$f_{i-80\text{m}}$	0.51	0.38	0.02	0.01	0.08	0	0

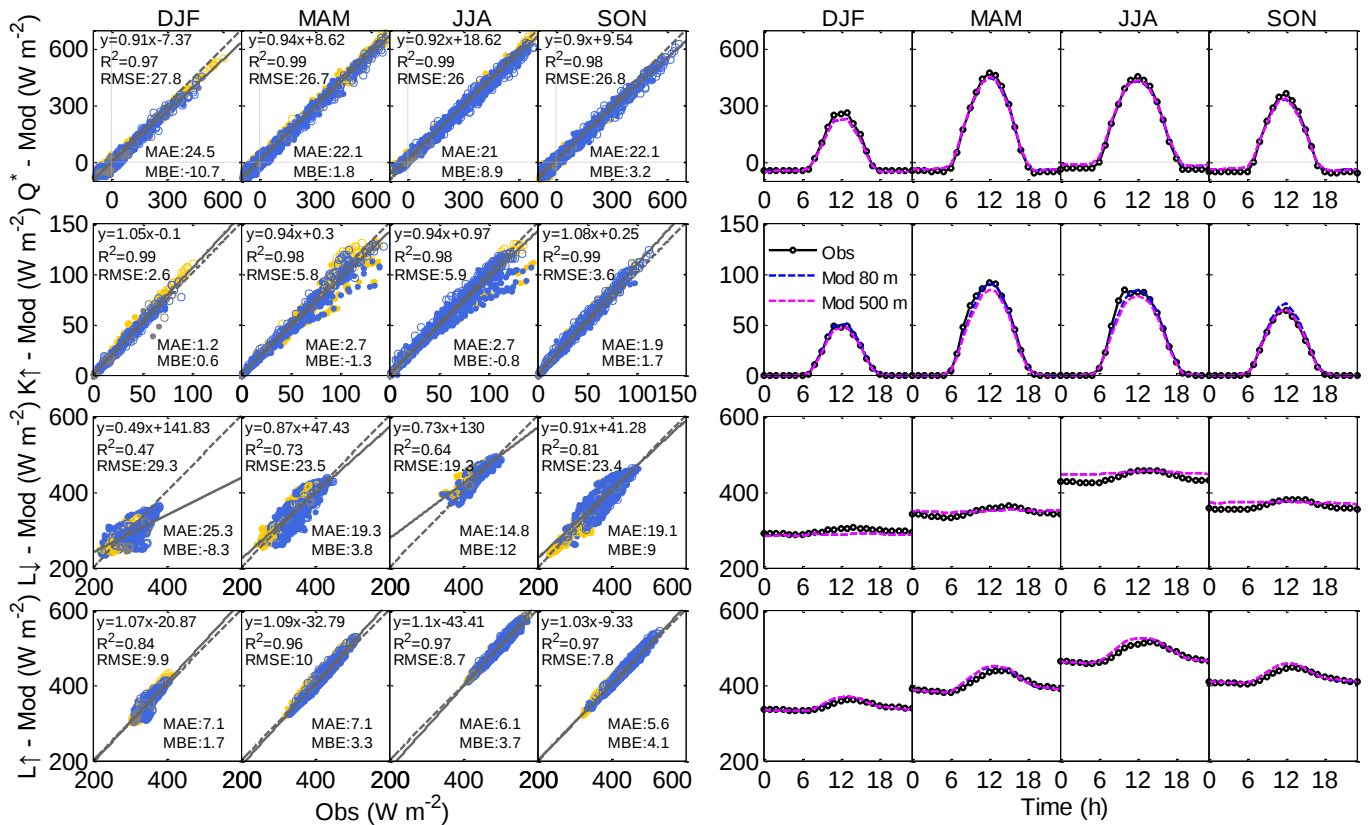


Figure 11. Observed and modelled radiation fluxes at XJH site by season (columns): (left) FOV 80 m with performance metrics under all-sky conditions (linear regression (solid), 1:1 (dotted), MBE, MAE RMSE (W m⁻²) for midday hours 11:00-13:00 LST (open circles), other hours (solid) under clear (yellow), cloudy (blue), rainy (grey) sky conditions. (right) mean diurnal behaviour using parameters for the FOV 80 m (blue), FOV 500 m (pink) and observed (black).

4. Conclusions

From analysis of radiative fluxes stratified by sky conditions for a central business district of Shanghai the key findings are:

- Given the latitude of this site, the annual range of median daytime maxima of incoming solar radiation (from 575 (winter) to 875 W m⁻² (spring)) is much smaller than for higher latitude cities, as expected.
- Cloud cover fraction and type both have a significant impact on the radiation fluxes. In Shanghai, this is especially evident in June with the East Asian rainy season when opacus clouds are frequent. Most evident is the reduction of incoming shortwave radiation in June by 350 W m⁻². As expected, the radiative fluxes are more variable, as quantified by the IQR, under cloudy and rainy conditions than for clear conditions.

- Incoming long-wave radiation is larger under cloudy conditions, as expected, thereby reducing radiative cooling at night. The average increase compared to clear sky condition for the four seasons (winter, spring, summer, autumn) was about 30, 18, 15, 60 W m⁻² and 53, 50, 5, 88 W m⁻² under cloudy and rainy conditions, respectively.
- Median daily maximum values of Q* under clear conditions range from about 400 (winter) to 640 W m⁻² (spring).
- Midday (11:00 - 13:00 LST) incoming shortwave radiation normalized by the total solar radiation flux received at the top of the Earth's atmosphere (τ), ranged between 0.6 - 0.7 under clear conditions, and decreased steadily from winter to spring to summer to autumn (0.69, 0.68, 0.64 and 0.63). Under cloudy conditions, the midday τ values were 0.47, 0.59, 0.49 and 0.48 in winter, spring, summer and autumn, respectively. For rainy days, the monthly midday τ values were often much lower, from 0.10 - 0.47.
- Increased atmospheric aerosol loading under haze conditions results in a decrease of τ by about 0.07 (11.3%).
- Midday surface albedo values under clear conditions are 0.128, 0.141, 0.143 and 0.129 for winter, spring, summer and autumn, respectively. There is a strong positive correlation with the solar elevation angle. The surface α for solar elevation angles <44° decreases from rainy to cloudy to clear conditions, whereas for solar elevation angles > 44° the inverse occurs, albeit the differences for the cloud conditions are smaller.
- As cloud cover fraction increases, the surface albedo is impacted, especially when cloud fraction is larger than 40%. The lower albedo values calculated during summer were caused by higher transmissivity with larger incoming shortwave radiation flux.
- The surface albedo varies most with solar elevation angle and azimuth angle due to heterogeneity of the urban surface at this site. A bulk surface albedo of 0.14 was calculated to represent the overall characteristics of this site across radiative conditions. This is similar to other dense cities.
- Individual tall buildings casting shadows have a dominant impact, reducing the albedo. This is particularly evident in the late afternoon (given the position of the buildings relative to the measurement site) and in winter (with lower solar elevation angles).
- The observed data when used to evaluate the NARP sub-model of SUEWS, show that NARP/SUEWS can reproduce the overall net all wave radiation fluxes at this site well. However, more attention needs to be directed to the long-wave fluxes in conditions of high humidity.

These radiation measurements are the first full year of data published for a central business district in China. The results are important in filling the gap of long-term radiation measurements in East Asian and low-latitude cities and provide a data set for evaluation of a range of urban land surface schemes of broad utility to urban planners and decision makers.

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