Observed Relationships Between the Urban Heat Island, Urban Pollution Island, and Downward Longwave Radiation in the Beijing Area

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Abstract We used the mean air temperature and particulate matter concentration at northern and southern rural stations as rural background values to calculate the urban heat island intensity (UHII) and urban pollution island intensity (UPII) for Beijing. The correlation between UHII and UPII is significantly negative in winter during the daytime and nighttime when selecting southern rural background stations but significantly positive in spring during both daytime and nighttime and in winter during the nighttime when selecting northern rural background stations. The downward longwave radiation (DLR) is highly correlated with surface air temperature and water vapor, and with particulate matter concentration in winter and summer. Water vapor also has a high correlation with particulate matter concentration in winter and summer. Winter data were used to investigate the particulate matter contribution to DLR to minimize the effect of humidity. The results indicate that in winter the urban area DLR and net radiation increased more than rural area under polluted conditions compared with clean conditions, which may lead to an increase in UHII. But in other seasons with more moisture, the aerosol effect on DLR is smaller than water vapor. Our results imply that the contribution of air pollutants to DLR had been overestimated in recent studies without removing water vapor effects on the longwave radiation. We suggest that the interaction between the urban heat island and the urban pollution island and related mitigation strategies needs to be carefully studied in the future by considering different climate zone and seasons.

1. Introduction

The urban heat island (UHI), where an urban area is warmer than the surrounding rural areas, has been widely noted and studied (Chen et al., 2003; Dou & Miao, 2017; Hu et al., 2016; Oke, 1982; Smoliak et al., 2015; Zhang et al., 2011; Zhou et al., 2014; Zhou et al., 2016). The UHI and the influence of aerosols on the UHI are undergoing increasing scrutiny (Chen et al., 2018; Lai & Cheng, 2009; Pandey et al., 2012; Rao, 2014; Sarrat et al., 2006; Wu et al., 2014; Wu et al., 2017; Yang et al., 2020). Because of human activities, urban air tends to be more polluted than rural air; this effect is referred to as an urban pollution island (UPI) (Crutzen, 2004) or urban particulate matter island (UPMI) (Huang et al., 2019). UHI produces warmer temperatures, which increase the turbulence and planetary boundary layer (PBL) height; this in turn can decrease the pollutant concentration near the surface (Li et al., 2018). In contrast, lower temperatures can decrease turbulence mixing and the PBL height, which can increase the pollutant concentration near the surface (Li et al., 2018; Petäjä et al., 2016). A UHI can produce a UHI circulation, which is a near-surface wind flow from the surrounding rural area into an urban area; this can influence air pollutant distribution and UPI (Agarwal & Tandon, 2010; Li et al., 2018).

On the other hand, a UPI can increase aerosol radiative forcing in an urban area. The downward longwave radiation (DLR) was found to be greater at urban sites, which have more polluted air (Estournel et al., 1983; Suckling, 1981; Wang et al., 2015). Higher concentrations of aerosol particles can scatter more solar radiation and reduce the amount of solar radiation at the ground (Che et al., 2014, 2018; Huang et al., 2015; Jin et al., 2010; Liu et al., 2007; Yu et al., 2016). In addition, infrared radiation emitted by the Earth can be trapped in urban areas by the increased amount of aerosols owing to the scattering and re-emission of more longwave radiation to the urban surface (Wang et al., 2016, 2018). Aerosols primarily affect the temperature through ground-atmosphere turbulent heat transfer (Jacobson, 1998). Pollution has been assumed to be chiefly responsible for this transfer by absorbing much of the outgoing longwave radiation from the
surface and re-emitting a significant fraction back (Oke et al., 2017). However, different studies have disagreed on the role of air pollutants for longwave radiation transfer back to the surface. Work in Montreal, Canada, has suggested that air pollutants have a minor role compared to the UHI effect, which results in a warmer urban boundary layer (UBL) largely through convective processes (Oke, 1982; Oke et al., 2017). Deng et al. (2016) suggested that aerosols mainly affect shortwave radiation and only slightly affect longwave radiation. Cao et al. (2016) considered the increased DLR due to the increased number of UPI-related aerosol particles to be the main reason for the stronger UHI effect. Water vapor, the most important greenhouse gas, largely absorbs terrestrial longwave radiation and emits part of it back to the surface (Ruckstuhl et al., 2007). The contributions of water vapor are larger than other gases (Yamada et al., 2012). Water vapor varies depending on the land use and land cover and may cause an urban dry-island or urban wet-island by urban-rural humidity difference (Dou et al., 2014; Holmer et al., 2013; Holmer & Eliasson, 1999). The urban-rural humidity difference can lead to the urban-rural DLR difference contributed by water vapor and affect UHI. But few studies have considered the contribution of water vapor to DLR while discussing aerosol influences on UHI.

Cao et al. (2017) found a positive correlation between ΔLST (i.e., difference between the remotely sensed land surface temperature of an urban area and adjacent rural areas) and ΔAOD (i.e., difference between the aerosol optical depths of an urban area and adjacent rural areas) especially at night. Li et al. (2018) observed a negative relationship between the UHII and urban-rural difference in near-surface aerosol concentrations during the summer in Berlin. This phenomenon was explained as the result of UHI-related enhancements in sensible heat flux and roughness promoting the turbulent dispersion of aerosol particles in the urban areas. Jonsson et al. (2004) also observed a negative correlation between the nocturnal UHI intensity and concentration of particulate matter in Dar es Salaam, Tanzania. Unlike Berlin, the air pollution in Beijing is attributed not only to local sources but also air pollutants transported from surrounding areas, especially Hebei Province and Tianjin, south of Beijing (Zheng et al., 2015; Zheng, Xu, et al., 2018). The aerosol concentration in and around Beijing is normally higher in the southern rural areas than in the urban and northern rural areas (Li et al., 2016). This causes the pollution island position to shift southward from the UHI position. In this study, we used rural background stations at northern rural areas or southern rural areas to calculate the intensities of UHI and UPI and estimate their correlation. We examined the impact factors of DLR and investigated its effects on UHI related to pollutants.

The rest of this paper is organized as follows. Section 2 presents the collected data and methods. Section 3 presents our investigation of the diurnal and monthly variations in the UHI and UPI and their relationship. We also discuss the relationship between DLR, specific humidity (q), and particulate matter (PM2.5) concentration. In section 4, we discuss DLR, q, and air temperature relationships especially in winter. Then we investigate DLR and net radiation (NR) under polluted and clean conditions, and discuss aerosols contributions on DLR and NR in urban and suburban areas. In section 4, a haze episode as a case study is investigated to better understand the effect of the UPI on the UHI and their relationship in detail. Section 5 presents the conclusions.

2. Data and Methods

2.1. Data

To calculate the urban pollution island intensity (UPII) and urban heat island intensity (UHII) with more representativeness, we selected 14 automatic weather stations (AWS) of the Beijing Meteorological Service (BMS) and 17 air quality stations of the Beijing Municipal Ecological Environment Bureau (BMEEB) distributed throughout the core urban area and rural areas to the north and south (Table 1 and Figure 1).

In consideration of the topography, built-up area, and population of Beijing, we selected only rural stations north and south of the main urban area as the rural background stations for UHI and UPI. In addition, we used downward and upward shortwave and longwave radiation data at two meteorological tower sites: the 325-m-tall tower of the Institute of Atmospheric and Physics (IAP), Chinese Academy Sciences, and the 36-m-tall tower at the Miyun Meteorological Bureau (i.e., MIY tower). At the IAP tower, three pyrgeometers and pyranometers (CNR1, Kipp & Zonen) were mounted at heights of 47, 140, and 280 m. At the MIY tower, one CNR1 (Kipp & Zonen; same type as at the IAP tower) was mounted at a height of 36 m. Before installation, all CNR1s were calibrated by the manufacturer. Both the IAP tower and MIY tower have been
Meteorological site | Latitude | Longitude | Site type |
--- | --- | --- | --- |
CHP | 40.217 | 116.231 | Northern rural |
HUR | 40.328 | 116.628 | Northern rural |
MIY | 40.371 | 116.832 | Northern rural |
DIL | 40.292 | 116.221 | Northern rural |
QIM | 39.899 | 116.395 | Urban |
TIT | 39.866 | 116.407 | Urban |
WAS | 39.878 | 116.352 | Urban |
YOD | 39.876 | 116.394 | Urban |
DOS | 39.939 | 116.483 | Urban |
XIZ | 39.954 | 116.349 | Urban |
GUY | 39.929 | 116.339 | Urban |
NAS | 39.933 | 116.483 | Urban |
AOT | 39.982 | 116.397 | Urban |
NOZ | 39.937 | 116.461 | Urban |
YOL | 39.712 | 116.783 | Southern rural |
YUF | 39.521 | 116.337 | Southern rural |
LIL | 39.581 | 116.03 | Southern rural |
CHP | 40.377 | 116.864 | Northern suburban, tower |
XIF | 40.204 | 116.936 | Northern rural |
XIT | 40.173 | 116.346 | Northern rural |
YAS | 40.295 | 116.679 | Northern suburban |
SHZ | 40.136 | 116.181 | Northern rural |
GUY | 39.933 | 116.354 | Urban |
AOT | 39.982 | 116.397 | Urban |
GUG | 39.905 | 116.428 | Urban |
CHD | 39.945 | 116.291 | Urban |
MUX | 39.856 | 116.391 | Urban |
HOL | 39.926 | 116.481 | Urban |
FXU | 39.907 | 116.357 | Urban |
YOL | 39.677 | 116.776 | Southern rural |
YOL | 39.522 | 116.321 | Southern rural |
GXT | 39.806 | 116.469 | Microwave radiometer |
IAP | 39.974 | 116.371 | Urban, tower |

Note. For air quality sites, no altitude information could be obtained according to the source links http://106.37.208.233:20035/ and http://www.bjmemc.com.cn. 

The UHII is usually calculated from the difference between the surface air temperatures in an urban area and the surrounding rural or suburban areas. Unlike Zheng, Ren, et al. (2018), who used a single urban station and single rural station to calculate the UHII, we followed Yang et al. (2013) and Dou et al. (2015) by using the hourly averaged temperature difference between urban stations and rural stations as the mean UHII. Thus, we defined the hourly UHII as follows:

\[
UHII = T_U - T_{NR} \tag{1}
\]

\[
UHII = T_U - T_{SR} \tag{2}
\]

where UHII is the hourly UHII and UHII is use the northern and southern rural stations, respectively, as a background. \( T_U \) is the mean hourly temperature of all urban stations within the UCA, \( T_{SR} \) is the mean hourly temperature of two rural stations south of the UCA, and \( T_{NR} \) is the mean hourly temperature of five rural stations north of the UCA.

For the UPI, both local pollutants and transported pollutants from adjacent areas in Hebei Province and Tianjin contribute to Beijing’s air pollution (Zheng et al., 2015). The pollutant concentration is commonly higher south of Beijing than north of Beijing and is even higher than in the city center (Li et al., 2016). In other words, the UPI can differ greatly depending on where the background stations are located. Thus, we defined the hourly UPI as follows:

\[
UPI = PM_U - PM_{NR} \tag{3}
\]

\[
UPI = PM_U - PM_{SR} \tag{4}
\]

where UPI uses the northern and southern rural stations, respectively, as the background. PM is the mean hourly \( \text{PM}_{2.5} \) concentration of all urban stations in the UCA, and PM is the mean
hourly PM$_{2.5}$ concentration of three rural stations south of the UCA, and PM$_{NR}$ is the mean hourly PM$_{2.5}$ concentration of four rural stations north of the UCA.

3. Results

3.1. UHI, UPI, and Their Relationship

Figure 2a shows the monthly mean PM$_{2.5}$ concentrations for the urban, northern rural, and southern rural areas. PM$_{2.5}$ is the lowest for the entire 12-month period in northern rural areas. PM$_{2.5}$ is the highest in January–March and November–December in southern rural areas; in particular, it is much higher than PM$_{2.5}$ in other areas in the winter (December–February). That suggests that more pollutants came from the southern area and were transported to the urban and northern rural areas. The monthly variation in PM$_{2.5}$ in urban areas is similar to the PM$_{2.5}$ concentration of Zheng, Ren, et al. (2018) for urban areas.

Figure 1. Map of the topography around Beijing, China. The building areas (gray pixels), ring roads (red curve), air quality sites (red dots), meteorological sites (black squares), and meteorological tower sites (black triangles) used in this study are marked. The urban core area (UCR), the blue square in Figure 1a, includes the main urban area within the fourth ring road and is displayed in Figure 1b in more detail with bigger markers for the meteorological and air quality.
except in January–March. The difference can mainly be explained by that fact that we took seven urban stations to find the urban mean, but Zheng et al. only used one urban station. Further, data we used are not successive from February 2016 to March 2015, which may lead to the difference between two results. In rural areas, there is little similarity between our study and Zheng, Ren, et al. (2018); this is mainly because they used the Shangdianzi station as the background station, which is far from the UCA of Beijing and in the mountains. Clear differences were observed when we used Equations 3 and 4 to calculate UPIIS and UPIIN, as shown in Figure 2c. This implies that, except for the winter, the pollution in the urban area has a larger contribution from local sources than nonlocal sources. Figure 2b shows the annual hourly mean PM2.5 concentrations for the urban, northern rural, and southern rural areas. The diurnal PM2.5 variations differed for these three areas. For the urban area, the nighttime PM2.5 concentration is highest around 23:00 LST. The lowest is observed at 17:00 LST. During the daytime, the PM2.5 maximum occurs at 12:00 LST. This is consistent with previous studies (Li et al., 2018; Zheng, Ren, et al., 2018). In the northern rural areas, the nighttime PM2.5 concentration is highest around 21:00 LST. The lowest is at 07:00 LST. During the daytime, the PM2.5 maximum occurred at 13:00 LST. In the southern rural areas, the nighttime PM2.5 concentration was highest around 03:00 LST. The lowest was at 17:00 LST. During the daytime, the PM2.5 maximum occurred at 10:00 LST. This result is consistent with the rural background station in Berlin (Li et al., 2018). Figure 2d compares the diurnal UPIIS and UPIIN. UPIIS was negative, but UPIIN was positive during the whole day. This is why we used the northern and southern rural stations as references to calculate UPIIS and UPIIN rather than a single rural background station. Figures 2e and 2f show the monthly and hourly values, respectively, for UHII. To calculate UHII, data were used only when the 2-min average wind speed was equal to or less than 3 m/s for each station and total precipitation for all stations was less than 1 mm. The daily variations in the UHII from our study are consistent with the results of Zheng, Ren, et al. (2018) and Yang et al. (2013) for Beijing. The differences in the UHII when the northern rural and southern rural stations
are used as references were quite small compared to the differences in the UPII. In general, UHIIN is greater than UHIIS except in winter (Figure 2e).

The average elevation above mean sea level (MSL) of the northern rural stations is 55.4 m; in contrast, the average elevation of the southern rural stations is 24 m above MSL, which may have led to about 0.2°C temperature difference using a lapse rate of 6.5°C for every 1,000 m in elevation. Generally, the elevation differences among these stations are negligible. The reason for hourly UHIIN being higher than UHIIS from midnight to noon may be that the northern stations are closer to the mountains, so they would likely be affected by cold mountain breezes during that period. During daytime from 12:00 to 17:00, the hourly UHIIN and UHIIS are much close mainly due to turbulent mixing and temperature advection by southerly flows. Figure 3 and Table 2 indicate that UPIIN was positively correlated with UHIIN during the nighttime for all four seasons. This is consistent with the results of Zheng, Ren, et al. (2018), who also selected a northern rural station as the rural background station. In contrast, UPIIS showed a negative correlation with UHIIS during the daytime and nighttime for the four seasons, except for a minor positive correlation during the nighttime in autumn. This is consistent with results for Berlin (Li et al., 2018) but contradicts previous results for Beijing (Zheng, Ren, et al., 2018). The location-dependent UPII caused the contradicting relations between UPIIN and UHIIN and between UPIIS and UHIIS. For Berlin and Beijing, the diurnal variation of UHI is similar, but the time of the UPII maximum is reversed. The highest UPII occurs in the daytime in Berlin but at night in Beijing (Figure 2d).

Table 2
Correlation Coefficients Between UPII and UHI

|                  | Daytime          | Nighttime       |
|------------------|------------------|-----------------|
|                  | Annual | Spring | Summer | Autumn | Winter | Annual | Spring | Summer | Autumn | Winter |
| UPIIN and UHIIN  | −0.01  | 0.17   | −0.14  | 0.01   | −0.06  | 0.21   | 0.29   | 0.10   | 0.09   | 0.22   |
| UPIIS and UHIIS  | −0.43  | −0.23  | −0.13  | −0.21  | −0.46  | −0.40  | −0.16  | −0.08  | 0.03   | −0.48  |

Figure 3. Scatter plots of the UPI and UHI intensities based on the urban-southern rural contrast and urban-northern rural contrast during (a, b) daytime and (c, d) nighttime in winter.
3.2. Relations Between DLR, Air Temperature, PM$_{2.5}$, and $q$

In recent years, more studies (Cao et al., 2016, 2017; Li et al., 2018; Zheng, Ren, et al., 2018) based on statistical analysis of observation data have supported the hypothesis that urban haze pollution is a contributing factor to the UHII. A major hypothesis for the effect of pollution on the UHII is that aerosol particles increase the DLR to the surface, which increases the UHII (Oke et al., 2017). Aerosol particles absorb longwave radiation emitted by the surface and heat the atmosphere. The heated atmosphere re-emits more longwave radiation back to the surface. In other words, the DLR plays an important role in intensifying the UHII. Figure 4 shows the relation between the hourly DLR and the 2-m air temperature at MIY. The DLR at both the IAP tower (at heights of 47, 140, and 280 m, however, not shown) and MIY tower (at a height of 36 m) shows a strong correlation with the 2-m air temperature. The correlation coefficients are larger at night than during the daytime because of the absence of shortwave radiation and less anthropogenic heat released at night. This strong correlation between the DLR and surface air temperature also demonstrates that the former has an important role for understanding climate change related to the greenhouse effect (Oke et al., 2017; Yamada et al., 2012). The hourly PM$_{2.5}$ concentration was classified into four levels and marked with blue, gray, pink, and red dots in Figure 4. The colored dots at different PM$_{2.5}$ levels do not show obvious aerosol-related tendencies. In general, despite the PM$_{2.5}$ concentrations, the data points are generally close to the fitting lines. Only the blue dots, which represent clean air, are separated from the fitting line in the region with a DLR of less than 200 W/m$^2$ and temperature of less than $-10^\circ$C; these data were probably collected during the invasion of strong cold air masses.

Figure 5 shows the scatter plots of PM$_{2.5}$ and DLR for the four seasons. In winter, PM$_{2.5}$ and DLR show the highest correlation for the year with $R^2$ at 0.2638 for the MIY tower. A high correlation is also observed between PM$_{2.5}$ and DLR in the summer, which is the second-highest value for the four seasons. In spring and autumn, which have higher PM$_{2.5}$ concentrations than in the summer, the correlations between PM$_{2.5}$ and DLR are poor. The DLR is greatest in the summer (Figure 5), which suggests that water vapor may contribute the most to the DLR (Yamada et al., 2012). The correlation between PM$_{2.5}$ and DLR at night is higher than during the daytime in winter, summer, and spring (Table 3).

The DLR is determined by the thermal structure and composition of the atmosphere. Water vapor, carbon dioxide (CO$_2$), and clouds are considered the dominant contributors to the DLR (Ao et al., 2016; Yamada et al., 2012).
et al., 2012). Yamada et al. (2012) found that water vapor and clouds have relatively large contributions to the DLR while CO₂ contribution is relatively small. In our study, we first used the IWV data of a ground-based multichannel microwave radiometer (MMWR) at GXT to investigate the relation between the DLR and IWV. The MMWR can be used to profile the temperature and humidity and can continuously measure WV profiles to estimate the IWV (Sánchez et al., 2013). Previous results from GPS, MMWR, and radiosondes (Liou et al., 2001; Ruckstuhl et al., 2007; Van Baelen et al., 2005) have generally agreed within 1–2 mm of precipitable water vapor (PWV) or IWV. Because there was no IWV or PWV data near two tower stations and IWV is closely related to q (Ruckstuhl et al., 2007), we used q near or at the towers to compare with the DLR at the towers. We found that the DLR at the MIY tower can be estimated as a power law of the IWV retrieved by MMWR at GXT and q at MIY station with correlation coefficients \( r^2 = 0.80 \) (figure not shown) and \( r^2 = 0.86 \) (Figure 6a), respectively, for the hourly mean, which are lower than DLR approximated as a power law of the IWV and q with correlation coefficients \( r^2 = 0.96 \) and \( r^2 = 0.94 \) for the monthly mean under all sky condition (Ruckstuhl et al., 2007).

Water vapor varies depending on the land use and land cover (Dou et al., 2014). Hence, using the IWV at GXT, which is about 20 km from the IAP tower site and 70 km from the MIY tower site, will introduce more differences into the water vapor data and lower the correlation between the DLR and water vapor. The correlation coefficients \( r^2 \) between DLR and q at MIY site are 0.67, 0.20, 0.8, and 0.57 for spring, summer, autumn, and winter (Figure 6b), respectively. The correlation coefficient for summer is smallest of the four seasons because of mostly cloudy days and saturation of longwave absorption by water vapor in this season (Ruckstuhl et al., 2007). For cloud-free conditions, we only used hourly data from times that were manually

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**Figure 5.** Relationship between hourly data for DLR and surface PM$_{2.5}$ concentrations in (a) spring, (b) summer, (c) autumn, and (d) winter at the MIY tower site.

**Table 3**

| Correlation Coefficients Between DLR and PM$_{2.5}$ Where DLR Is at 36 m of MIY |
| Daytime | Nighttime |
|---------|-----------|
| Spring  | Summer    | Autumn | Winter | Spring  | Summer    | Autumn | Winter |
| 0.0893  | 0.1850    | 0.0015 | 0.2696 | 0.0226  | 0.2304    | 0.0003 | 0.2956 |

*Note.* PM$_{2.5}$ data were taken from the EPA monitoring station MIY, which are closest to the MIY tower station.
observed to have a total cloud cover less than 20%. The correlation coefficients $r^2$ for clean and polluted conditions without clouds are 0.86 and 0.78; the latter is lower because aerosols contributed more to DLR especially under lower humidity condition (Figure 7). Figure 8 shows the scatter plots of PM$_{2.5}$ and $q$ for the four seasons. The correlations between PM$_{2.5}$ and $q$ are significant in winter and summer with $r^2 = 0.51$ and 0.22, respectively. But in winter, $q$ is less than 5 g kg$^{-1}$ so that PM$_{2.5}$ has more effect on DLR (see Figure 7). At MIY tower, correlations between PM$_{2.5}$ and DLR and PM$_{2.5}$ and $q$ show the highest and the second highest correlations in winter and summer, respectively. Higher PM$_{2.5}$ concentrations in winter typically accompany higher water vapor mainly because of the positive feedback between PM$_{2.5}$ and water vapor. Increased relative humidity can enhance hygroscopic growth and multiphase reactions and lead to more secondary particulate matter (Tie et al., 2017; Liu et al., 2018). Thus, it may imply in winter the DLR contribution by PM is more significant than that in other seasons due to not only less water vapor effects but also more aerosols effects.

4. Discussion

4.1. Effects of water vapor and PM on DLR

In North China, PM pollution is generally accompanied by an increase in water vapor (Wang et al., 2019; Zhou et al., 2014). Our study also shows that the specific humidity is well correlated with PM$_{2.5}$, especially in the winter and summer (Figure 8). One explanation for this is that high humidity may enhance heterogeneous chemical reactions with highly concentrated mineral particles to increase the generation of secondary aerosols and lead to a higher PM concentration (Quan et al., 2014). Some studies (e.g., Wang et al., 2016) have shown that, with clear skies, the DLR can increase more than 10% on polluted days compared to clear days. This result does not remove the significant contribution of water vapor to the DLR, which has a significant positive correlation with the PM concentration. To investigate effects of PM on DLR by minimizing the effect of water vapor, we need to find a time period with minimal water vapor and significant PM influence. Figure 9a shows monthly $q$ at urban areas and northern and southern rural areas.
(i.e., December, January, and February), the monthly $q$ and $q_d$ differences between urban and rural areas are the smallest for the entire year. Mean hourly $q$ varies between 1.5 and 1.9 g kg$^{-1}$ at three different areas in winter (Figure 9b). The southern rural areas are the wettest. The urban area is as dry as the northern rural areas at night and the driest during the daytime. Figure 10 shows hourly mean 2-m air temperature, $q$, and DLR variations at IAP and MIY tower stations for all sky condition.

All data were separated by clean conditions (i.e., hourly PM$_{2.5}$ concentration less than 50 $\mu$g m$^{-3}$, blue lines) and polluted conditions (i.e., hourly PM$_{2.5}$ concentration greater than 50 $\mu$g m$^{-3}$, red lines). In general, both

![Figure 8](image)

Figure 8. Scatter diagrams plotting PM$_{2.5}$ versus $q$ at the MIY station: (a) spring, (b) summer, (c) autumn, and (d) winter. Data during rainy hours were omitted.

![Figure 9](image)

Figure 9. (a) Monthly mean specific humidity and (b) hourly specific humidity in winter for the urban stations (black square), northern rural stations (blue triangle), and southern rural stations (red triangle).
the urban site and rural site have more water vapor and DLR under polluted conditions than that under clean conditions. Without removing contributions of clouds, polluted aerosols can increase DLR around 10% under clean condition at both urban and rural sites, which agrees with Wang et al. (2016). The water vapor difference between the urban and the rural sites is very small without pollution and is relative larger with pollution, especially at night. The DLR difference between the urban site and the rural site is significant during daytime and is very small at night for clean conditions. At night under polluted conditions, DLR and $q$ at the urban site are slightly larger than at the rural site. In contrast, at night under clean conditions, differences between the urban site and rural site in both DLR and $q$ are very small. The difference in DLR between polluted conditions and clean conditions is considerably larger. This implies that due to the presence of air pollution and greater water vapor, the urban site receives more longwave radiation than the rural site which could lead to larger UHII and smaller UHII without pollution and with less water vapor at night. Using 1-year data, we calculated DLR and net radiation (NR) of the MIY and IAP tower sites for clear days (Table 4). Cloud cover and type were observed at the GXT observatory three times daily (8:00, 14:00, and 20:00). Figure 10. (a) Hourly mean air temperature, (b) specific humidity, and (c) downward longwave radiation (DLR) at MIY and IAP stations under clean (PM$_{2.5} \leq 50$, blue) and polluted (PM$_{2.5} > 50$, red) conditions in winter.

| Radiation (W/m$^2$) | Seasons | MY 36 m | IAP 47 m | IAP 140 m | IAP 280 m | Radiation difference (polluted-clean) |
|----------------------|---------|---------|---------|---------|---------|-------------------------------------|
| DLR                  | Clean   | 217     | 232     | 211.7   | 230.4   | 213.8                               |
| SSA                  | 295.6   | 295     | 290.1   | 287.6   | 304.5   | 298.9                               |
| SSAW                 | 257.8   | 268.2   | 254.4   | 268.1   | 266.4   | 277.9                               |
| NR                   | W       | 40.2    | –49.4   | 43.2    | –28.9   | 29.7                                |
| SSA                  | 124.2   | 18.1    | 137     | 31.3    | 137.8   | 20.7                                |
| SSAW                 | 83.8    | –10.6   | 94.4    | 10.8    | 92.3    | 2.8                                 |

Note: W: winter. SSA: spring, summer, and autumn. SSAW: spring, summer, autumn, and winter.

Table 4

Downward Longwave Radiation (DLR), Net Radiation (NR) Under PM$_{2.5} \leq 50$ (Clean), and PM$_{2.5} > 50$ (Polluted) Conditions at 36 m on the Miyun Tower and 47, 140, and 280 m on the IAP Tower.
Radiation Differences Between Clean (PM$_{2.5} \leq 50$) and Polluted (PM$_{2.5} > 50$) Conditions Under All Sky and Cloudless Conditions on the Miyun Tower (36 m) and IAP Tower (47, 140, and 280 m)

| Radiation difference (W/m$^2$) | Sky conditions | Seasons | MIY 36 m Suburban | IAP 47 m | IAP 140 m | IAP 280 m |
|-------------------------------|----------------|---------|-------------------|----------|-----------|-----------|
|                               |                | Urban   | Urban-suburban    | Urban    | Urban-suburban | Urban    | Urban-suburban |
| DLR$_{polluted-clean}$        | All sky        | W       | 28.5              | 31.7     | 3.2        | 30.9     | 2.4        |
|                               |                | SSA     | 5.3               | 6.2      | 0.9        | 9.4      | 4.1        |
|                               |                | SSAW    | 18                | 21.2     | 3.2        | 22.6     | 4.6        |
|                               | Cloudless      | W       | 15                | 18.7     | 3.7        | 19.5     | 4.5        |
|                               |                | SSA     | −0.6              | −2.5     | −1.9       | −5.6     | −5         |
|                               |                | SSAW    | 10.4              | 13.7     | 3.3        | 11.5     | 1.1        |
| NR$_{polluted-clean}$         | All sky        | W       | −51.7             | −38.5    | 13.2       | −32.2    | 19.5       |
|                               |                | SSA     | −39.2             | −43.2    | −4         | −38.8    | 0.4        |
|                               |                | SSAW    | −38.4             | −36.1    | 2.3        | −31.1    | 7.3        |
|                               | Cloudless      | W       | −89.6             | −72.1    | 17.5       | −64.8    | 24.8       |
|                               |                | SSA     | −106.1            | −105.7   | 0.4        | −117.1   | −11        |
|                               |                | SSAW    | −94.4             | −83.6    | 10.8       | −89.5    | 4.9        |

Note. W: winter. SSA: spring, summer, and autumn. SSAW: spring, summer, autumn, and winter.

The NR differences between clean and polluted conditions are 89.6, 72.1, 64.8, and 65.3 W m$^{-2}$ in winter at MIY at 36 m and IAP at 47, 140, and 280 m, respectively. Furthermore, the NR differences between clean and polluted conditions are 106.1, 105.7, 117.1, and 115 W m$^{-2}$ in other seasons at MIY at 36 m and IAP at 47, 140, and 280 m, respectively, which are higher than in winter. The definition of a clear-sky day we used does not completely preclude cloud cover, so there may be some cloud impact. Thus, this greater NR decreases can be ascribed to more water vapor, higher DLR (Figure 5), and more cloud-cover influence on radiation in seasons other than winter. The urban and rural DLR$_{PC}$ differences with clear wintertime conditions are 3.7, 4.5 and 4.5 W m$^{-2}$ when urban values used at 47, 140, 280 m on the IAP tower, respectively (Table 5). But the differences in DLR$_{PC}$ between urban and rural areas with cloudless conditions in other seasons are −1.9, −5 and −4.4 W m$^{-2}$ when urban values are used at 47, 140, and 280 m on the IAP tower, respectively. The differences of pollution contributions to NR (NR$_{PC}$) between urban and rural areas with cloudless conditions in winter are 17.5, 24.8, and 24.3 W m$^{-2}$ when urban values are used at 47, 140, and 280 m on the IAP tower, respectively. But the differences in NR$_{PC}$ between urban and rural areas with cloudless conditions in other seasons are 0.4, −11, and −8.9 W m$^{-2}$ when urban values are used at 47, 140, and 280 m on the IAP tower, respectively. It is worth noting that the contributions by air pollutants to DLR and NR, which results in positive feedback on the increase in UHII, are obvious only in winter. In other seasons (i.e., spring, summer, and autumn), air pollution has negative effects on UHII by radiation. These differences between winter and other seasons are caused mainly by water vapor differences. Figure 11 illustrates processes and feedbacks between pollutant concentration, planetary boundary layer (PBL) height, water vapor, DLR, and temperature. Processes 1–3 are a positive feedback mechanism which is fully described by Petäjä et al. (2016). Another positive feedback mechanism formed by processes 3–5 is explained by Tie et al. (2017) and Liu et al. (2018). Li et al. (2018) suggested that UPI is negatively correlated with UHI mainly via processes 1, 7, 8, 9, and 12. For process 6, water vapor has been proved to be one of the main contributors to DLR (Ruckstuhl et al., 2007; Yamada et al., 2012). Also, for process 7, more recent studies have found evidence of contributions by air pollution to DLR (Cao et al., 2016, 2017; Li et al., 2018; Wang et al., 2016). Our study focuses on processes 6 and 7 and discusses contributions to DLR by water.
vapor and pollutant concentration in order to more accurately estimate the contribution of pollution to DLR and its effects on UHII.

4.2. Discussion of a Haze Episode

We studied an 8-day-long haze episode to investigate the relations between the UHI, UPI, and DLR (Figure 12). The hourly PM$_{2.5}$ concentrations were taken from air quality stations at urban, southern rural, and northern rural areas and averaged to obtain urban mean (PM$_{2.5}$U), southern rural mean (PM$_{2.5}$SR), and northern rural mean (PM$_{2.5}$NR), respectively. Likewise, the hourly temperatures were taken from meteorological stations in the urban, southern rural, and northern rural areas and averaged to obtain $T_U$, $T_{SR}$, and $T_{NR}$, respectively. UPI$_{IS}$ and UPI$_{IN}$ were calculated using Equations 3 and 4. UHI$_{IS}$ and UHI$_{IN}$ were calculated using Equations 1 and 2. The 2-min northerly ($v$) wind component at YUF (southern rural site), AOT (urban site), and XIT (northern rural site) is also shown in Figure 12. During the episode, the PM$_{2.5}$ concentration was first below 100 $\mu$g/m$^3$ and then increased to almost 600 $\mu$g/m$^3$ before clearly diminishing at the end. UPI$_{IS}$ was more negative except during the periods N5, N7, D7, N8, and D8. UPI$_{IN}$ was more positive except during the periods D6, N8, and D8. The negative or positive values of both UPI$_{IS}$ and UPI$_{IN}$ were significantly affected by the wind. The variations in UHI$_{IN}$ were more consistent with those in UHI$_{IS}$. The UHII sharply increased around sunset and decreased around sunrise when the variations in PM$_{2.5}$U, PM$_{2.5}$SR, and PM$_{2.5}$NR showed a high correlation during N1–N4 as the wind was calm. UPI$_{IN}$ increased after sunset and decreased after sunrise because more pollutants in the urban area were compressed by the lower PBL height (Petäjä et al., 2016). In addition, the northerly relatively clean mountain breeze reduced air pollutants in the northern rural area, which led to a high UPI$_{IN}$ at night. During daytime, convective PBL mixing reduced PM$_{2.5}$U, PM$_{2.5}$SR, and their fluctuations. These variations in UPI$_{IN}$ and UHI$_{IN}$ demonstrated obvious correlations. Unlike UPI$_{IN}$, UPI$_{IS}$ decreased after sunset and increased after sunrise. In general, the areas south of the Beijing urban area are pollutant sources (Li et al., 2016) and had more pollutants.

Figure 11. Diagram of relations, processes (digital number in circle), and feedbacks between pollutant concentration, planetary boundary layer (PBL) height, water vapor (H$_2$O), downward longwave radiation (DLR), surface temperature, and air temperature.
than the urban area, which led to a low negative UPIIS during nighttime. During the daytime, convective PBL mixing also reduced PM$_{2.5}$U, PM$_{2.5}$SR, and their deviation, which led to a higher negative UPIIS. These variations in UPIIS and UHIIS led to their distinct negative correlations. We compared the DLRs at 47-m height at the IAP tower and at 36-m height at the MIY tower and $q$ at AOT and MIY. The DLR deviation between IAP (urban station) and MIY (northern rural station) was positive at night and negative during the daytime, which corresponds to a high nighttime UHII and low daytime UHII. In contrast, the magnitude of the DLR deviation did not correlate well with the magnitude of UHIIN. The deviation of $q$ showed a good relationship with the DLR deviation, which is in accordance with the statistical results in section 4. During some periods (e.g., N5, N6, and D6), PM$_{2.5}$U, PM$_{2.5}$SR, and PM$_{2.5}$NR

![Figure 12. Evolution of (a) PM$_{2.5}$ for urban, southern rural, and northern rural sites; (b) UHIIN and UPIIN; (c) UHIIS and UPIIS; (d) $v$-component of horizontal wind at XIT (northern site), AOT (urban site), and YUF (southern site); and (e) DLR difference (black line) and difference between the specific humidity $q$ (red line) of the IAP tower and MY tower. N1–N8 and D1–D8 correspond with nighttime (gray stripes) and daytime (white stripes), respectively.](10.1029/2020EA001100)
varied differently, which caused complex variations in the UHI, UPI, DLR deviation, and \( q \) deviation. This may have led to a poor correlation between the UHI and UPI.

5. Conclusions
This study discusses the relationship between UPI and UHI in Beijing. Unlike the study in Berlin (Li et al., 2018), our results show that the correlation between UHII and UPII is significantly negative in winter during the daytime and nighttime when selecting southern rural background stations but significantly positive in spring during both daytime and nighttime and in winter during the nighttime when selecting northern rural background stations. The reason is mainly due to different pollutant concentrations in northern rural areas, urban area, and southern rural areas in Beijing. Thus, we suggest that in order to investigate UPI, UHI, and their relationships, one needs to carefully select a rural background station taking such factors into account as pollutant emissions, distributions, topography, and so forth. Our study also shows that DLR is highly correlated with surface air temperature and \( q \) and with PM\(_{2.5}\) concentration in winter and summer. Water vapor also has a high correlation with PM\(_{2.5}\) concentration in winter and summer, which implies water vapor enhanced hygroscopic growth and multiphase reactions and led to more production of secondary particular matter. To minimize water vapor's effect on DLR, only data in winter with less water vapor have been analyzed to estimate the contribution by pollutants to the DLR. In winter, air pollution contributes 15, 18.7, 19.5, and 19.5 W m\(^{-2}\) to DLR at MIY at 36 m and at IAP at 47, 140, and 280 m, respectively. Our result at MIY is very close to a previous study in rural areas (Cao et al., 2016). The NR differences between clean and polluted conditions are 89.6, 72.1, 64.8, and 65.3 W m\(^{-2}\) at MIY at 36 m and at IAP at 47, 140, and 280 m, respectively. In winter, the differences in pollution contributions to DLR (DLRP\(_{C}\)) between urban and rural areas with cloudless conditions are 3.7, 4.5, and 4.5 W m\(^{-2}\) when urban values are used at 47, 140, and 280 m on the IAP tower, respectively. But in other seasons, the differences in DLRP\(_{C}\) are negative. In winter, the differences of pollution contributions to NR (NRP\(_{C}\)) between urban and rural areas with cloudless conditions in winter are 17.5, 24.8, and 24.3 W m\(^{-2}\) when urban values are used at 47, 140, and 280 m on the IAP tower, respectively. But in other seasons, the differences in NRP\(_{C}\) are negative as well. That implies that pollutant radiative effects can enhance DLR and NR distributions in urban areas more than in rural areas, leading to increased UHII only in winter. Nevertheless, a haze episode case study shows that the PBL evolution and wind advection dominate the variation in the UPII and play an important role in the difference between UHII in northern rural areas and UHII in southern rural areas.

Our results imply that air pollutant’s contributions to DLR had been overestimated in recent studies without removing water vapor effects on the longwave radiation. Thus, this may enlarge the effect of UPI on UHI. Because complex relations, processes, and feedbacks exist among pollutant concentration, PBL height, water vapor, DLR, and air temperature (Figure 11), designing mitigation strategies for UHI should be carefully treated. Additionally, the effects of air pollutants on DLR need further evaluation using, for example, more observations and modeling studies.

Data Availability Statement
The PM\(_{2.5}\) data are available on the website of Ministry of Ecology and Environmental of the People’s Republic of China (http://106.37.208.233:20035). Other data, including two towers observation data and AWS data, are available at http://www.iium.cn/dataCenter/.

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