PM$_{2.5}$ Pollution Modulates Wintertime Urban Heat Island Intensity in the Beijing-Tianjin-Hebei Megalopolis, China

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Abstract Heavy PM$_{2.5}$ (particulate matter with aerodynamic diameter equal to or less than 2.5 $\mu$m) pollution and urban heat island (UHI) pose increasing threats to human health and living environment in populated cities. However, how PM$_{2.5}$ pollution affects the UHI intensity (UHII) has not been fully understood. The impacts of PM$_{2.5}$ on the wintertime UHII in the Beijing-Tianjin-Hebei megalopolis of China are explored during 2013–2017. The results show that the UHII at the time of daily maximum/minimum temperature (UHII$_{\text{max}}$/UHII$_{\text{min}}$) exhibits a decreasing/increasing tendency as PM$_{2.5}$ concentration increases, causing a continuous decrease in the diurnal temperature range. These effects are mediated via aerosol-radiation interaction (aerosol-cloud interaction) under clear-sky (cloudy) condition. The changes in PM$_{2.5}$ concentration further cause different relative trends of UHII$_{\text{max}}$/UHII$_{\text{min}}$/diurnal temperature range across different cities in the Beijing-Tianjin-Hebei region, which are likely related to the differences in both the PM$_{2.5}$ composition and city size. This study provides insights on how air pollution affects urban climate and would help to design effective mitigation strategies.

Plain Language Summary A detailed understanding of the relationship between PM$_{2.5}$ (particulate matter with aerodynamic diameter equal to or less than 2.5 $\mu$m) and the urban heat island (UHI) effect is significant for climate change adaption, planning, and sustainable development in urban regions. While the Beijing-Tianjin-Hebei (BTH) megalopolis of China is among the areas with the highest population densities and fastest urbanization rates in the world, the impacts of PM$_{2.5}$ pollution on UHI, along with their regional differences in the BTH megalopolis, remain unclear. This study demonstrates that different PM$_{2.5}$ concentrations in the BTH region pose various influences on the UHI intensities and change rates in different cities of varying sizes. The UHI intensities during daytime and nighttime, respectively, exhibit weakening and strengthening tendency as PM$_{2.5}$ concentration increases. These effects are mediated via aerosol-radiation interaction under clear-sky condition and aerosol-cloud interaction in cloudy weather. The relative changes in the UHI magnitudes were mainly determined by PM$_{2.5}$ composition and city size. The asymmetrical influences of PM$_{2.5}$ on the daytime and nighttime UHI intensities caused continuous decreases in the diurnal temperature ranges in the urban areas as the pollution level increased. Our study improves the understanding of urban climate affected by air pollution and provides a scientific basis for the mitigation of UHI impacts.

1. Introduction Fine particulate matter, that is, particulate matter with aerodynamic diameter equal to or less than 2.5 $\mu$m (PM$_{2.5}$), is considered as one of the most important air pollutants degrading air quality (Kim et al., 2006; Pongpiachan et al., 2013; Tiwari et al., 2014; Xing et al., 2017; Zheng, Xu et al., 2018). It endangers the urban environment and the health of residents due to its complicated composition and properties (Gu et
The relationship between air pollutants and the urban heat island (UHI, i.e., elevated urban air/surface temperatures compared to those in rural surroundings, most prominently present during nighttime) has also attracted attention from the scientific community (Cao et al., 2016; Crutzen, 2004; Jonsson et al., 2004; Luo & Lau, 2018; Wu et al., 2017; Zheng, Ren, et al., 2018). A detailed understanding of the relationship between PM$_{2.5}$ and the UHI effect is of great significance for adapting urban climate change, urban planning, and the development of urban sustainable ecosystem (Cao et al., 2016; Oke et al., 2017; Thornes, 2001; Roth, 2010; Velasco & Roth, 2012; Yoshikado & Tsuchida, 1996; Zhao et al., 2014; Zhou et al., 2008).

Some previous studies indicated that particulate matter intensified the UHI effect, for example, by warming the urban atmosphere and changing the stability and vertical movement of the planetary boundary layer (PBL; Menon et al., 2002) and reducing the amplitude of diurnal temperature fluctuations (Travis et al., 2002). Jonsson et al. (2004) found that UHI intensity (UHII) and particulate matter concentration in Dar es Salaam, Tanzania, exhibited a positive correlation in the nighttime. Cao et al. (2016) examined the corresponding relationship between the satellite-based aerosol pollution and land surface UHII in cities of varying sizes in northern China and estimated that the contribution of pollutants to the land surface UHII at night reached 0.7 ± 0.3 °C. Recently, Chen et al. (2018) also found that the UHII in Beijing was enhanced by 16.7% during polluted days in winter. However, other studies reported opposite effects of particulate matter. Sang et al. (2000) and Chistoforou et al. (2000) suggested that the dust dome formed by particulate matter over a city produced an energy imbalance in the urban boundary layer, with a positive correlation between the concentrations of PM$_{2.5}$ and “urban cool island” (i.e., negative UHII which is sometimes observed during daytime). Shades from tall buildings in the city center are primarily responsible for the daytime urban cool island (Yang, et al., 2017), while high-concentration aerosols in the urban boundary layer also may cause an additional cooling radiation effect in the daytime (Chen et al., 2003). Wu et al. (2014, 2017) suggested that the PM$_{2.5}$ concentration in the atmosphere had a weakening effect on the UHII, but such influence was limited only to the lowest 500–1,000 m. In addition, Deng et al. (2002) suggested that the UHI effect primarily arises from the effects of atmospheric warming by anthropogenic heat and the changes in the underlying urban surface properties, but the cooling effect due to PM$_{2.5}$ also cannot be neglected.

Recently, Zheng, Ren, et al. (2018) revealed that the downward shortwave radiation at the surface decreased with the increase in PM$_{2.5}$ concentration in Beijing, leading to a weaker daytime UHII, but a stronger nighttime UHII. Until now, there is a gap in the understanding of the impacts of PM$_{2.5}$ pollution on UHI with their regional differences in the Beijing-Tianjin-Hebei (BTH) region of China (Li et al., 2004; Ren et al., 2008, 2017; Zhou et al., 2015), which is among the areas with the highest population densities and fastest urbanization rates in the world. The PM$_{2.5}$ pollution in the BTH region remains at a characteristically high level in recent years, especially in winter due to the elevated heating emissions and unfavorable meteorological conditions, e.g., clam or light wind, high humidity, temperature inversion, low PBL, and weak local or large-scale atmospheric circulation (Guo, He, et al., 2016; Guo, Miao, et al., 2016; Wang et al., 2014; Yang et al., 2018; Zhang et al., 2012, 2016; Zheng et al., 2012). Under the given geographical and climatic conditions, the influence of PM$_{2.5}$ on the wintertime UHII for cities in different sizes still merits further observation and investigation in the BTH region.

In the present study, we consider four cities in the BTH region, including Beijing and the adjacent cities of Tianjin, Langfang, and Baoding (Figure 1a), which exhibit similar geographic and climatic background conditions. Using environmental and meteorological observations over the period of 2013–2017, the objective is to investigate the influences of different PM$_{2.5}$ concentrations on the UHIIs and to reveal their relative changes across different cities with various sizes in the BTH megalopolis.

## 2. Data and Methodology

### 2.1. Data

Nine urban stations and 10 representative rural stations were selected (Figure 1b), as suggested by previous studies and satellite-based station classifications (Huang et al., 2013; Li, Shi, et al., 2015; Liu et al., 2005; Ren.
et al., 2008; Wang et al., 2013; Yang, Ren, et al., 2013; Yang, Wu, et al., 2013). The geographic locations, elevations, and We have collected at the different sites with type-selection methods are supplied in Text S1 and Table S1 in the supporting information (SI).

We have collected the daily PM$_{2.5}$ mass concentrations and the sequences of daily average, maximum, and minimum temperature ($T_{\text{ave}}$, $T_{\text{max}}$, and $T_{\text{min}}$), rainfall, and cloud fractions in different cities during the winter periods of the 5 years from 2013 to 2017. The winter season is defined as the period from 1 December of a year to 28 February of the following year. The air-temperature data after quality control were homogenized and provided by the National Meteorological Information Center (Li, Yang, et al., 2015). In addition, surface solar radiation was only recorded at the Beijing (BJ) station, a national reference climatological station in the urban area of Beijing. To match the observation of cloud cover recorded every three hours during daytime [i.e., at 0800, 1100, 1400 and 1700 local solar time (LST)], surface solar radiations were firstly chosen at the BJ...
station at these five episodes. Then, to further exclude the effects of both morning fog and diurnal variation of solar radiation (i.e., low solar radiation during early morning and late afternoon hours), surface total and scattered radiation observations only at 1100 and 1400 LST were chosen to explore the relationship between downward shortwave radiation and the PM$_{2.5}$ concentrations at the BJ station. The PM$_{2.5}$ concentrations and meteorological observations were obtained from the Ministry of Ecology and Environment of China and China Meteorological Administration, respectively. Monthly emissions of black carbon at a resolution of $0.25^\circ \times 0.25^\circ$ were provided by the Multiresolution Emission Inventory for China updated in 2016 (Zhang et al., 2009). The monthly emission of black carbon around urban stations was calculated from the grid cell in which the respective station is located.

2.2. Methods

We first analyzed the distribution characteristics of PM$_{2.5}$ concentration at all stations in the four cities. In the context of the air-quality standard of the environment of the People's Republic of China (GB 3095–2012), the extent to which a change in PM$_{2.5}$ concentration affects the UHII was investigated at three different air-quality levels. To exclude the possible influence of meteorology, the UHII and PM$_{2.5}$ samples in four cities under different weather conditions were considered (Text S1 and Tables S2 and S3). In particular, light or calm wind condition, clear-sky, and cloudy condition with nonrainfall were compared.

PM$_{2.5}$ and UHI samples with daily-averaged wind speeds $>$ 3.3 m/s were excluded (according to the Beaufort wind-force scale). Days with daily total cloud cover $\leq$20% were treated as clear sky (Lou et al., 2019; Zhang et al., 2018); otherwise, they were labeled as cloudy conditions (cloud cover $>$20%). Taking Beijing as an example, Figure S1 in the SI shows that for wind speed $\leq$3.3 m/s, PM$_{2.5}$ still decreased with increasing wind speed, while the UHI as expected showed no obvious change, as opposed to wind speed $>$3.3 m/s. The UHII is dependent on wind speed, as shown by many existing studies (e.g., discussions in Oke et al., 2017). The UHII decreases as wind speed increases, and the largest effects appeared when wind speeds $>$2 m/s. In what follows, the relationships between PM$_{2.5}$ and UHII were compared under different cloud cover conditions.

We defined UHII as the averaged difference of surface air temperature between urban and the corresponding rural stations (i.e., urban minus rural), hereafter referred to as UHII$_{ave}$, UHII$_{max}$, and UHII$_{min}$ for $T_{ave}$, $T_{max}$, and $T_{min}$, respectively, (Figure 1 and Table S1 in the SI; Luo & Lau, 2017, 2018; Ren et al., 2008; Yang et al., 2011; Yang, Ren, et al., 2013; Yang, Wu, et al., 2013). With the different sizes of four selected cities and the different selections of rural stations, it is inappropriate to directly compare the magnitudes of the absolute UHII values between different cities. Therefore, we calculated the relative change in the UHII for each city and defined the change rate (CR) of UHII as

$$CR = \frac{\text{UHII}_H - \text{UHII}_L}{\text{UHII}_L} \times 100\%$$

where UHII$_L$ and UHII$_H$ denote the UHII under low (slight or moderate) and high (moderate or heavy) pollution levels, respectively. Also, the analysis of variance test was conducted to assess the statistical significances of the differences of UHII under different PM$_{2.5}$ pollution levels.

To assess the similarities or differences in the temporal distribution patterns of PM$_{2.5}$ observed at all the air-quality observatory sites, the coefficient of divergence (COD) was calculated (See Text S3; Limbeck et al., 2009; Pongpiachan & Iijima, 2016). A COD value approaching zero indicates a strong similarity of emission sources between two sites, while a COD close to one implies the dissimilarity of two assessed observatory sites.

3. Results

3.1. Characteristics of PM$_{2.5}$ Distribution

Over the most recent 5 years, the average wintertime PM$_{2.5}$ concentrations in Beijing, Tianjin, Langfang, and Baoding City were 82.7, 91.4, 105.8, and 159.4 $\mu$g/m$^3$, respectively (Figure S2a). All four cities exhibited relatively low COD values (Text S3 and Table S4), suggesting that there are no huge differences in PM$_{2.5}$ pollution patterns across these cities. The probability distribution function of daily PM$_{2.5}$ concentrations shows that the PM$_{2.5}$ concentrations of the largest probability in Beijing, Tianjin, and Langfang was
approximately 50 μg/m³, while it was located in the range of 100–150 μg/m³ in Baoding (Figure S2b). Due to similar climate and geographic conditions, the distributions of PM_{2.5} concentration in different cities should be highly consistent. Therefore, it is reasonable to infer that the highest PM_{2.5} concentrations in Baoding probably depend on the different compositions of energy consumption and the characteristics of emission sources (Fan et al., 2013; Guo et al., 2014; Liu et al., 2016; Zhang et al., 2012).

3.2. A Typical Case Study in Beijing

Taking a PM_{2.5} pollution episode recorded at the BJ station as an example, Figure 1c shows the observed hourly wind speed (WS), PM_{2.5}, and UHII during 27–29 December 2017. PM_{2.5} concentrations observed at two rural stations in Beijing city (Daxing and Shangdianzi) were selected to represent the rural areas. The hourly wind speed was lower than 3 m/s throughout the whole period, with no cloud at most times, so possible effects of dominant weather conditions on the UHII can be excluded. Figure 1c also indicates distinct urban-rural differences in PM_{2.5} concentrations but less so for WS, implying that the changes in UHII should be attributable to the relatively high PM_{2.5} concentrations in the urban areas. The PM_{2.5} concentration gradually increased during these days (Figure 1c). The daily-averaged PM_{2.5} increased from 62.8 μg/m³ on 27 December to 112.8 μg/m³ on 28 December, before reaching 192.7 μg/m³ on 29 December, corresponding to the deterioration in air quality from slight to moderate and then to heavy pollution. Accordingly, UHII_{ave} gradually decreased, varying from 2.9 °C on 27 December to 2.82 °C on 28 December and to 2.67 °C on 29 December, corresponding to the CR of UHII_{ave} of −54.3% and −25.1%, respectively, and UHII_{max} (UHII_{min}) weakened (enhanced) gradually. These results suggest that UHII decreases with increasing PM_{2.5} concentration, consistent with the observations of Zheng, Ren, et al. (2018).

3.3. Statistical Characteristics

Figure 2 shows the distributions of UHII_{ave}, UHII_{max}, and UHII_{min} associated with different PM_{2.5} levels in four cities under both clear-sky and cloudy conditions. Except for coastal Tianjin, where the weather condition was frequently disturbed by the sea-land breeze (Huang et al., 2013), in other three cities the UHII_{ave}, UHII_{max}, and UHII_{min} intensities increased with the city sizes (Figures 1b and 2). Moreover, as the PM_{2.5} concentration increased, there were relatively large changes in the UHII across the various cities. For example, under clear-sky (cloudy) condition, when the air quality in Beijing worsened from slight to moderate pollution, and then to severe pollution, UHII_{max} decreased from 0.78 (0.71) °C to 0.72 (0.56) °C and then to 0.55 (0.44) °C, while UHII_{min} increased from 3.14 (2.84) °C to 3.31 (2.87) °C and then to 3.55 (3.04) °C; UHII_{ave} weakened from 2.58 (2.14) °C to 2.57 (2.00) °C and then decreased to 2.49 (1.83) °C. For UHII_{ave}, its trends with increasing PM_{2.5} concentrations are different across various cities under both conditions (Figures 2e and 2f). UHII_{ave} decreased as PM_{2.5} concentrations increased in Beijing and Baoding, but a reverse relationship was observed in Tianjin and Langfang under clear-sky condition. While UHII_{max} (UHII_{min}) exhibited a consistent weakening (enhancing) tendency as the PM_{2.5} concentrations increased in all four cities under both conditions (Figures 2a–2d). These features are more significant when PM_{2.5} pollution deteriorated from slight to severe levels (See Table S8).

According to equation (1), we calculated the CR values of UHII corresponding to the change in pollution level under both conditions, and the results are shown in Figures 3a–3d. In detail, when PM_{2.5} pollution changed from slight to moderate level, UHII_{max} exhibited a consistent negative trend, with the magnitude varying from 7.45% to 32.5% (from 21.2% to 31%) under clear-sky (cloudy) conditions. In contrast, UHII_{min} indicated a positive trend, with its magnitudes ranging from 5.41% to 38.0% (1.05% to 38.5%) under clear-sky (cloudy) conditions. Under both clear-sky and cloudy conditions, the influences of PM_{2.5} change on UHII_{max} (UHII_{min}) were much larger in the cities with more severe pollution (Figures 2 and 3a–3d and Table S8). With a change from moderate to severe level in PM_{2.5} pollution, the trends in UHII_{max} (UHII_{min}) were similar to those with the slight-to-moderate change (Figures 3a–3d). Also, the relative changes in UHII were heterogeneous under both above conditions. These results suggest that the changes in PM_{2.5} concentration affected the UHI magnitude. Under both weather conditions, with worsening air pollution UHII_{max} in all four cities was markedly weakened and UHII_{min} was strengthened. Note that UHII_{ave} was mainly subject to the comprehensive influences of UHII_{max} and UHII_{min}, but the four cities did not show consistent trends in UHII_{ave}. 

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4. Discussion

The effect of atmospheric pollution on urban climate is mainly determined in both direct and indirect ways, known as aerosol-radiation interaction and aerosol-cloud interaction, respectively. First, particles exert direct effects on the climate by scattering or absorbing solar radiation (Ding et al., 2016; Gu et al., 2006, 2010; Huang et al., 2018; Li et al., 2017; Wu et al., 2017; Zhang et al., 2010). Second, they modify the optical properties of clouds, cloud distributions in the form of cloud condensation nuclei, cloud fraction, and its lifetime, thus influencing the climate indirectly (Huang et al., 2014; Li et al., 2016; Liao et al., 2015; Small et al., 2011; Zhao et al., 2017).

To explore the effects of aerosol-radiation interaction and aerosol-cloud interaction, we examine the relationship of total and sunny diffuse radiations with PM$_{2.5}$ at 1100 and 1400 LST under clear-sky and cloudy conditions. Total (sunny diffuse) radiation decreased (increased) with increasing PM$_{2.5}$ concentrations, suggesting that aerosol reduced surface total radiation via absorbing and scattering processes (Figures 3e and 3f), consistent with simulation results (Gu et al., 2006, 2010; Wu et al., 2017; Zhu et al., 2018). Through these aerosol-radiation interactions, UHHI$_{\text{max}}$ exhibited a consistent weakening tendency as surface total solar radiation decreased (diffuse radiation increased) with increasing PM$_{2.5}$ concentration in all four cities (Figure 2). The CRs (i.e., slopes) under clear-sky condition were
even larger than those under cloudy condition, indicative of that clouds possibly confound the PM$_{2.5}$ effect on radiation.

Figure 3g further depicts the relationship between aerosol and cloud fraction over the BTH region. On the one hand, cloud fraction increased with increasing PM$_{2.5}$ concentration in four cities (Figure 3g),
probably indicating that PM$_{2.5}$ mainly affected the UHII through aerosol-cloud interactions, that is, aerosol indirect effect (Small et al., 2011; Fan et al., 2016; Guo et al., 2018; Li et al., 2016; Yang, Wang et al.,; Zhao et al., 2017). Cloud fraction is generally higher when PM$_{2.5}$ pollution is more severe (Figure 3g), showing that aerosol-cloud interactions may be more prominent, resulting in a likely longer cloud lifetime and more cloudiness (Fan et al., 2016; Zhao et al., 2017). These interactions reduce daytime incoming shortwave radiation at the surface and trap more upward longwave radiation from the surface and emit more downward longwave radiation to warm the near-surface atmosphere during nighttime. This effect will easily lead to a smaller (larger) daytime (nighttime) UHII. On the other hand, PM$_{2.5}$ is more easily accumulated with the lower and more stable PBL that can be suppressed by high cloud cover conditions (Guo, He, et al., 2016; Guo, Miao, et al., 2016; Lou et al., 2019), as demonstrated by the positive correlation between PM$_{2.5}$ concentration and cloud fraction (Figure 3g). As a result, aerosol-cloud interactions could further enhance the PM$_{2.5}$ concentration (Zhao et al., 2017), which is beyond the scope of the present study.

Moreover, here we have explored the relative change in UHII associated with different pollution levels in four cities. It was found that, as the particle concentration increased, daytime UHII$_{\text{max}}$ was weakened, and nighttime UHII$_{\text{min}}$ was enhanced under both clear-sky and cloudy conditions. The opposite influences of PM$_{2.5}$ pollution on the daytime and nighttime UHII significantly reduced the diurnal temperature range (DTR) in the urban area as the pollution increased to serious levels under both weather conditions (Tables S5 and S6). This pattern is also one of the main reasons for the asymmetrical temperature change observed in the study region and the variations in the DTR (Karl et al., 1991; Liu et al., 2004; Vose et al., 2005; Xue et al., 2019). Such an asymmetrical influence is meaningful in researches of urbanization related to air pollution in the BTH region and on the regional climate.

Furthermore, previous studies pointed out that the compositions of the pollutants and the sizes of particulate matter were different in various cities, thus inducing different longwave and shortwave radiation effects (Gu et al., 2006, 2010; Huang et al., 2018; Liao et al., 2015; Liu et al., 2018). Based on radiative transfer simulation (Zhu et al., 2018), the mean ratios of negative/positive shortwave radiative forcing due to different aerosol types to that caused by the total the aerosol loading are indicated as follows: sulfate (35.57%) > organic carbon (20.94%) > black carbon (19.56%) at the surface, while black carbon (37.5%) > organic carbon (35.36%) > sulfate (1.8%) in the near-surface layer (Text S4 and Table S7). The aerosol-induced cooling/warming effects at the surface/the near-surface are consistent with our observational investigation (Figures 3e and 3f) and the results in previous studies (Gu et al., 2006; Huang et al., 2018). In addition, Ding et al. (2016) and Gao et al. (2016) revealed that black carbon can induce heating in the PBL, particularly in the middle-upper PBL, and the resultant reduced surface heat flux substantially depressed the development of PBL. In general, black carbon and organic carbon in the PBL have strong absorbing properties, which induce both the prominent surface cooling and near-surface warming, whereas sulfate has a strong scattering capacity, which cools the surface and results in a weaker near-surface warming (Ding et al., 2016; Gu et al., 2006; Huang et al., 2018; Zhu et al., 2018). In this study, we showed that, in heavily polluted cities such as Langfang and Baoding, particularly when PM$_{2.5}$ pollution changes from slight to moderate/severe level (Figure 3 and Table S8), the negative (positive) correlation between the PM$_{2.5}$ concentration and UHII$_{\text{max}}$ (UHII$_{\text{min}}$) was more prominent, and the DTR was much smaller under both clear-sky and cloudy conditions (Table S6). Compared with Beijing, Baoding has a larger emission of black carbon (Figure S3; Liu et al., 2016) and higher concentrations of organic/elemental carbon and sulfate/nitrate in the aerosols (See Text S5; Fan et al., 2013; Guo et al., 2014; Zhang et al., 2012). It implies that Baoding possibly experienced a larger magnitude of shortwave radiation effects induced by PM$_{2.5}$, for example, cooling surface and warming near-surface or upper PBL in the daytime, even though PM$_{2.5}$ concentrations in Beijing and Baoding were somehow similar.

Therefore, via the effects induced by both aerosol-radiation interaction and aerosol-cloud interactions (Figures 3e–3g), the influences of PM$_{2.5}$ on the variations in UHII were more prominent in more polluted cities such as Baoding and Langfang (Figure S2). Given a similar change in PM$_{2.5}$ pollution levels, larger CR values in these two cities may be related to the PM$_{2.5}$ composition and its proportion, as discussed above. It should also be noted that a small city with smaller UHII baseline (e.g., Baoding and Langfang; see
Figure 2) may result in a larger CR value, and the influence of city size on the relative change in UHII cannot be neglected.

In addition, some specific synoptic patterns might also cause noticeable changes in both UHII and PM$_{2.5}$. Synoptic patterns can affect air quality episodes which are already expressed through the meteorological variables (e.g., temperature, wind speed, rainfall, and cloud cover), and thus, these variables can represent a certain synoptic situation over a given region (Kassomenos et al., 2003; Luo et al., 2018; Miao et al., 2018; Ning et al., 2018; Shahgedanova et al., 1998; Wang, Liu, et al., 2019; Yang Yim et al., 2019; Zheng et al., 2015). The possibly different associations between the UHII and PM$_{2.5}$ under different synoptic patterns will be the focus of a future study.

5. Conclusions

In this study, we analyzed daily observations in the winters of 2013–2017 in Beijing, Tianjin, Langfang, and Baoding to understand how PM$_{2.5}$ influences UHII. We found that as PM$_{2.5}$ concentrations increased, observed UHII$_{\text{max}}$ (UHII$_{\text{min}}$) in all four cities exhibited decreasing (increasing) tendency under both clear-sky and cloudy conditions. The asymmetrical influences of increasing PM$_{2.5}$ pollution on daytime and nighttime UHIIs directly induced continuously decreasing DTR in the urban area. As the level of PM$_{2.5}$ pollution increased, the relative changes in UHII were heterogeneous under both clear-sky and cloudy environments. The changes in UHII are especially larger in the cities with heavier pollution, particularly when the air quality changes from slight to severe level. More severe PM$_{2.5}$ pollution are accompanied by increased cloud fractions and prolonged cloud lifetime (i.e., aerosol indirect effects), thereby reducing shortwave radiation at daytime and increasing longwave radiation that warms near-surface atmosphere during nighttime. These changes generated smaller daytime UHII and larger nighttime UHII, and caused the continuous decreases in DTR. In addition, given a similar change in the PM$_{2.5}$ pollution level, the differences in both PM$_{2.5}$ composition and city size somewhat determined the relative changes in UHII and DTR in the BTH region.

Our further examinations reveal that the PM$_{2.5}$ changes affected UHII through aerosol-radiation interaction under clear-sky condition and via aerosol-cloud interactions under cloudy condition. Our present work improves the understanding of urban climate affected by air pollution and may provide a scientific basis for the mitigation of UHII impacts in the BTH regions. The finding reported here should also have important implications for other urban regions experiencing serious air pollutants.

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