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# Interaction between urban heat island and urban pollution island during summer in Berlin

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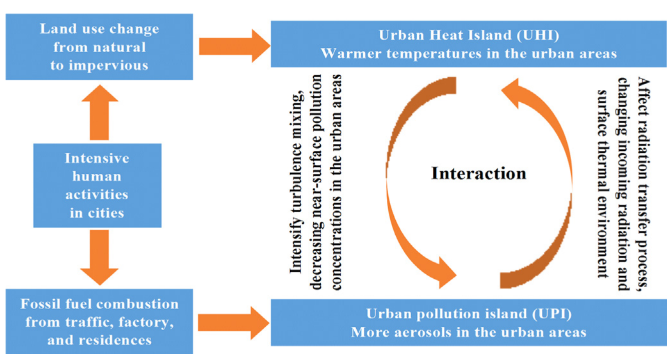
## HIGHLIGHTS

- Interaction between urban heat island and urban pollution island was studied.
- The impact of urban heat island on near-surface PM10 concentrations was investigated.
- The urban-rural differences in the incoming solar radiation and atmospheric longwave radiation were analyzed.
- The response of urban heat island to the urban-rural difference in absorbed radiation was quantified.

## GRAPHICAL ABSTRACT

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## ABSTRACT

Urban Heat Island (UHI) and Urban Pollution Island (UPI) are two major problems of the urban environment and have become more serious with rapid urbanization. Since UHI and UPI can interact with each other, these two issues should be studied concurrently for a better urban environment. This study investigated the interaction between the UHI and UPI in Berlin, through a combined analysis of in-situ and remote sensing observations of aerosols and meteorological variables in June, July, and August from 2010 to 2017. The atmospheric UHI (AUHI), surface UHI (SUHI), atmospheric UPI (AUPI), and near-surface UPI (NSUPI) were analyzed. The SUHI and AUPI are represented by the remote sensing land surface temperature (LST) and aerosol optical depth (AOD), and the AUHI and NSUPI are represented by the in-situ air temperature and Particulate Matter (PM10) concentrations. The study area shows spatial consistency between SUHI and AUPI, with higher LST and AOD in the urban areas. UHI strengthens the turbulent dispersion of particles in the urban areas, decreasing the NSUPI. The NSUPI intensity shows a negative relationship with the AUHI intensity, especially at night with a correlation coefficient of −0.31. The increased aerosols in urban atmosphere reduce the incoming solar radiation and increase the atmospheric longwave radiation in the urban areas. The response of the surface to the change of absorbed radiation is strong at night and weak during the day. This study estimates that the SUHI intensity is enhanced by around 12% at clear night by the increased absorbed radiation in the urban areas using an attribution method.

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The goal of this paper is to strengthen the understanding of the interactive influence between UHI and UPI and provide a basis for designing mitigation strategies of UHI and UPI.



## 1. Introduction

Intensive change of land use and emissions of air pollutants are two of the most important aspects of human activities in urban areas (McDonnell and MacGregor-Fors, 2016). The change of land surface from natural to impervious alters surface properties, resulting in lower albedo, higher Bowen ratio (ratio of sensible and latent heat flux), and larger energy storage of the surface in urban areas. As a result, urban areas produce warmer temperatures than the surrounding rural areas, which is called Urban Heat Island (UHI) phenomenon (e.g. Rizwan et al., 2008; Chakraborty et al., 2017). Meanwhile, the combustion of fossil fuels from factories, cars and other transportation means, as well as the daily human behaviour in cities emit a large number of pollution particles into the urban atmosphere (e.g. Ohara et al., 2007; Bonn et al., 2016). Thus, the urban atmosphere has more pollution particles than the rural atmosphere, which is called Urban Pollution Island (UPI) phenomenon (Crutzen, 2004). UHI increases the heat stress of city dwellers (e.g. Gabriel and Endlicher, 2011), while UPI increases the exposure of people to air pollutants (e.g. Monn and Becker, 1999; Han and Naeher, 2006). Furthermore, the superposition of heat stress and air pollution makes individuals more susceptible to the effect of each respective threat (e.g. Lai and Cheng, 2010; Meng et al., 2012; Burkart et al., 2013).

UHI and UPI can interact with each other. UHI-related warm temperatures can promote the dispersion of aerosol particles to higher atmospheric boundary level by increasing turbulent mixing (Sarrat et al., 2006). A temperature reduction in urban areas could decrease the rate of turbulent mixing and the height of mixing layer (Fallmann et al., 2016), leading to higher near-surface concentrations of PM10 (Fallmann, 2014). In turn, UPI-related increased aerosols in the urban atmosphere can generate larger radiative forcing. On the one hand, the increased aerosols can scatter more solar radiation back to space and reduce solar radiation reaching the urban surface (e.g. Jin et al., 2010; Wang et al., 2015). On the other hand, the increased aerosols can trap more earth-emitted infrared radiation and re-emit more longwave radiation to the urban surface (e.g. Lubin and Simpson, 1994; Cao et al., 2016). The UPI-induced larger radiative forcing in urban areas affects the urban thermal environment and changes the UHI. Cao et al. (2016) reported that the haze in semi-arid Chinese cities enhanced the surface UHI intensity by 0.7 K at night.

Considering the interaction of UHI and UPI is important for a comprehensive understanding of the urban environment. However, most of the previous studies on UHI and UPI were conducted separately. Insufficient knowledge of the interaction between UHI and UPI inhibits the development of integrative mitigation strategies. Nowadays, fast urbanization process further strengthens UHI and UPI (e.g. Wei and Ye, 2014; AAAS, 2016). The interactive impacts of growing UHI and UPI are becoming a new direction for future studies (Crutzen, 2004). Baklanov et al. (2016) reviewed the previous studies on the complex interactions between climate, air quality, and megacities, and addressed the importance of the integrated studies of urban climate and air pollution in the changing climate. Recent European project MEGAPOLI focused on the feedbacks and interlinkages between climate change and regional air quality related to megacities (Baklanov et al., 2010). In China, the study of the interaction between air pollution and the physical state of the atmospheric boundary layer was taken as a priority study area of boundary layer meteorology (Lee et al., 2015). The modelling of urban air pollution and climate interactions was widely discussed in the 9th International Conference in Air Quality - Science and Application (Sokhi et al., 2017).

In this study, we attempted to connect UHI and UPI and carried out an integrated study of these two problems in the city of Berlin, Germany. In-situ and remote sensing observations of aerosols and meteorological variables in June, July, and August from 2010 to 2017 were collected. The atmospheric UPI (AUPI), near-surface UPI (NSUPI), atmospheric UHI (AUHI), and surface UHI (SUHI) were analyzed. The AUPI describes the urban-rural difference of the aerosol optical depth (AOD) from remote sensing observation, and the NSUPI describes the urban-rural difference of the near-surface aerosol concentrations characterized by the in-situ observation of Particulate Matter (PM10). The AUHI describes the urban-rural difference of the air temperature from in-situ observation, and the SUHI describes the urban-rural difference of the land surface temperature (LST) from remote sensing observation. The study consists of three sections. Firstly, the relationship between the SUHI and AUPI in spatial variations was investigated using remote sensing data. Secondly, the impact of the AUHI on the NSUPI was examined using in-situ observations. Thirdly, the impact of the AUPI on the radiation transfer was studied by comparing the incoming solar radiation and atmospheric longwave radiation between the urban and rural areas. Moreover, the response of the SUHI to the urban-rural difference of the absorbed radiation was analyzed using an attribution method (Cao et al., 2016). Given the strong UHI (Fenner et al., 2014) and the good quality of remote sensing observation under cloudless conditions in the summer of Berlin (Li et al., 2018), this study only focuses on the summer period in June, July, and August. The goal of this study is to improve the understanding of the interactive influence between urban thermal environment and air pollution, and provide a scientific basis for the mitigation of these two problems.

## 2. Study area, datasets, and methodology

### 2.1. Study area

The study area is Berlin, the capital city of Germany. Berlin (52.34°–52.68° N, 13.10°–13.77° E) is located in Northeastern Germany and covers an area of around 900 km$^2$. Berlin has a temperate maritime climate with the annual mean temperature of 9.5 °C and annual precipitation of 591 mm. Affected by the prevailing westerlies, the wind mainly comes from the west directions in summer (Fig. S1). Berlin has >3.6 million inhabitants, with one-third living in the inner city. Based on Corine land cover datasets (Feranec et al., 2007), around 35% of the area is covered by buildings, and around 20% of the area is covered by transportation/infrastructure in Berlin (Fig. 1a). Most of the non-urban area is covered by forest and farmland. The large built-up area creates distinct AUHI (e.g. Fenner et al., 2014; Li et al., 2017) and SUHI in this city (e.g. Li et al., 2017, 2018). The UHI-enhanced heat wave has a negative impact on the health of the Berlin dweller (Gabriel and Endlicher, 2011; Scherer et al., 2014). Meanwhile, Berlin suffers from air pollution. The air quality cannot meet the standards of the European Union in terms of PM10 (Görgen and Lambrecht, 2007). The local emissions are the dominant source of the elevated urban particulate number and mass concentrations (Bonn et al., 2016). The fine mode aerosols are the dominant component of PM10, accounting for around three-quarters of the observed PM10 mass. Road traffic is the major emission source, due to a large number of vehicles (Lutz, 2013) and a dense traffic network in Berlin (Fig. 1.b). In 2015, 1.37 million motor vehicles were registered in the city (389 cars per 1000 residents). The traffic intensity is high in the urban center and low in the rural areas. The urban-rural differences in the emissions and air pollutants are significant (Kuik et al., 2016).