Relieved air pollution enhanced urban heat island intensity in Yangtze River Delta, China

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Abstract

The National Air Pollution Control Plan promoted in China since 2013 successfully reduces the concentrations of air pollutants, especially for PM₂.₅ (aerosol particles with aerodynamic diameters equal to or less than 2.5 μm). The reduction of PM₂.₅ levels may impact the urban heat island (UHI) intensity as the existence of fine particles can affect the energy balance of the earth–atmosphere system. In this paper, the effect of the pollution control plan on the urban heat island intensity in Yangtze River Delta of China was investigated via observational analysis and numerical modeling. The observational data showed that PM₂.₅ concentrations in megacities (Shanghai, Nanjing, Hangzhou, Hefei) in Yangtze River Delta were around 35 μg m⁻³ in 2017, which was reduced by about 48.36%, 28.25%, 29.41% and 32.5% compared to 2014. PM₂.₅ reduction over the urban centers corresponded well to strengthened UHI intensities during the day and weakened UHI intensities at night-time. The daytime UHI intensity was increased by up to 1 K, and the night-time UHI intensity was reduced by up to 1 K when the PM₂.₅ levels decreased from 2014 to 2017. Numerical simulations confirmed this ‘seesaw effect’ on the daytime and night-time UHI intensity due to reduced PM₂.₅ caused by the increased surface downward shortwave radiation and top of atmosphere outgoing longwave radiation. In summary, the air pollution control plan noticeably reduced PM₂.₅ levels and thus affected UHI intensity, which should be considered in future studies on urban climate and environmental planning.

Keywords: PM₂.₅; Urban heat island; WRF-Chem; Yangtze River Delta

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1. INTRODUCTION

Rapid industrialization and urbanization in the last decades have changed land cover, surface albedo and anthropogenic heat flux as well as air pollutant concentrations in China (Xia et al., 2014). These changes have significantly impacted the urban heat island (UHI) effect, which refers to the increased surface temperature over urban areas compared to the surrounding areas (Howard, 1833; Manley, 1958; Oke, 2002). UHI is a local phenomenon and distinct from large-scale global warming trends (Jones et al., 1990; Peterson et al., 1999). It affects the boundary layer and the underlying surface energy balance (Lin et al., 2008), as well as wind patterns (Hjelmfelt, 2017), precipitation (Zhong et al., 2017) and sensible heat convection efficiency (Zhao, et al., 2014). The UHI also has a significant impact on air pollutants by producing local wind patterns that cause urban centers to suffer even more severe air pollution (Agarwal and Tandon, 2010). Meanwhile, human activities with the growing population result in the increase of air pollutant emissions (Wang, et al., 2006). This results in an uneven distribution of air pollutants, including PM$_{2.5}$, in the urban center and suburban district, which in turn feeds back on the UHI.

Increased population and anthropogenic activities in the urban centers have made PM$_{2.5}$ (aerosol particles with aerodynamic diameters equal to or less than 2.5 $\mu$m), PM$_{10}$ (aerosol particles aerodynamic diameters equal to or less than 10 $\mu$m), ozone (O$_3$), carbon monoxide (CO), sulfur dioxide (SO$_2$), and nitrogen dioxide (NO$_2$) well known as the main air pollutants in China in the recent years. PM$_{2.5}$ is the dominant factor causing hazy weather and the primary atmospheric particulate pollutant (Liang et al., 2014). PM$_{2.5}$ scatters and absorbs solar radiation and thus affects the climate by changing the energy balance of earth–atmosphere system (Kaufman et al., 2002;
Nabat et al., 2014; Zhang et al., 2010). According to the national observation data collected from 74 big cities in the Bulletin on Environmental Conditions in China, annual PM$_{2.5}$ concentrations in these cities ranged from 26-160 $\mu$g m$^{-3}$ and only 4.1% of those cities satisfied air quality standards in 2013. Since then, the Chinese government has promoted the National Air Pollution Control Plan to relieve this situation and successfully reduced the concentration of air pollutants, especially PM$_{2.5}$. In the last four years, the national annual average PM$_{2.5}$ concentrations decreased from 72 $\mu$g m$^{-3}$ (in 2013) to 62 $\mu$g m$^{-3}$ (in 2014), 55 $\mu$g m$^{-3}$ (in 2015) and 47 $\mu$g m$^{-3}$ (in 2016) (MEE, 2013; MEE, 2014; MEE, 2015; MEE, 2016;).

Fine particles (PM$_{2.5}$) directly reduce solar radiation, leading to a decrease in the surface temperature of up to 1 K (Im et al., 2012; Hu and Liu, 2017). The temperature decrease also depends on PM$_{2.5}$’s chemical composition, which determines whether the particles only scatter light or also absorb it. As sulfate aerosols are purely scattering, the surface temperatures decrease when the sulfate concentrations increase (Harris and Highwood, 2011; Qian and Giorgi F, 2000; Solomon et al., 2011). Black carbon is the atmospheric aerosols’ main absorbing component and may reduce the cooling effect of aerosols as it can warm the atmosphere at the top of the boundary layer (Schult et al., 1997; Wu et al., 2008; Chang and Park, 2004). A large number of studies show that aerosol properties also have significant regional characteristics (Jia et al., 2015; Wu et al., 2013). Zhuang et al (2014) investigated the aerosol particles of Nanjing based on observational data and pointed out that the aerosol particles in the urban center showed strong absorbing ability while those in the suburban area had a strong scattering ability. The inherently different PM$_{2.5}$ loads and compositions between the urban center and suburban area resulted in different radiation forcing.
(Zhuang et al., 2014; Zhuang et al., 2015), thus causing different effects on the surface temperature in these two regions.

Although various investigations focused on the aerosols’ radiative forcing and climate effects, the regional impact of PM$_{2.5}$ on UHIs is rarely investigated. Cao et al. (2016) found increased longwave radiation emitted by an aerosol layer would intensify the night-time UHI according to remote sensing temperature data from 39 cities in China. Our previous study showed that differences in the PM$_{2.5}$ loads in the urban center and suburban region reduced the daytime UHI intensity based on one-year observational data and numerical simulations in Nanjing (Wu et al., 2014; Wu et al., 2017). However, a long-term observational data analysis is still lacking. The PM$_{2.5}$ reductions resulting from the Air Pollution Control Plan in the last four years could possibly cause a daytime increase and a night-time decrease of UHIs. This means that the control plan may introduce a “seesaw pattern” to the UHIs in daytime and night-time.

To comprehensively understand the PM$_{2.5}$ impact on UHIs, we use long-term and multi-site observational data as well as numerical modelling in this paper. In particular, we investigate how the Air Pollution Control Plan affects the UHI intensity when reducing the air pollution in Yangtze River Delta. The Yangtze River Delta (YRD) is not only one of the most developed regions in China with the highest city density and urbanization level but also the largest adjacent metropolitan areas in the world (Hu et al., 2009). In the last four years, the air pollutant concentrations in YRD have been reduced by the Air Pollution Control Plan as the regional average PM$_{2.5}$ concentration decreased from 67 $\mu$g m$^{-3}$ (in 2013) to 60 $\mu$g m$^{-3}$ (in 2014), 53 $\mu$g m$^{-3}$ (in 2015) and 46 $\mu$g m$^{-3}$ (in 2016) (MEE, 2013; MEE, 2014; MEE, 2015; MEE, 2016). Four megacities with
spreading urbanization as Nanjing (NJ), Hangzhou (HZ), Shanghai (SH) and Hefei (HF) in YRD are taken to be the target cities, and we analyze a record of four-year surface temperatures and PM$_{2.5}$ concentrations.

In the following sections, $T_{UHI}$ (the surface UHI intensity) refers to the difference in the surface temperature at the urban and suburban stations. A larger $T_{UHI}$ corresponds to a more intense UHI effect. We define $\Delta T_{UHI}$ (the difference in $T_{UHI}$ between the simulations with and without the air pollution control) as the change in the UHI intensity due to the Air Pollution Control Plan, quantifying the control plan effect on UHI intensity. A positive value of $\Delta T_{UHI}$ indicates that the UHI intensity is strengthened by the conduct of the control plan. The variable $\Delta T$ is used to represent the surface temperature changes with and without the control plan, with positive values of $\Delta T$ representing a higher surface temperature when the control plan is present. $\Delta SW$ refers to the downward shortwave radiation changes at the surface caused by the air control plan, and a positive value means that the conduction of the plan results in the surface receiving more solar radiation in the daytime due to the decrease of PM$_{2.5}$ concentration. We also define $\Delta LW$ as the TOA outgoing longwave radiation changes with and without the control plan, a positive value indicates more radiation emitted by the atmosphere which means the earth-atmosphere system would cool down in the night.

2. METHODOLOGY

2.1 OBSERVATIONAL DATA

This study period is from 1st of January 2014 to 31st of December 2017. The hourly surface temperature data and the hourly PM$_{2.5}$ concentration data were collected separately from the
Meteorological Bureau and the Environmental Monitoring Center of NJ, HZ, SH and HF. All the PM$_{2.5}$ sites are located near the surface temperature observation sites and the distances between them are small, so we only show surface temperature sites of the four cities in this paper. The altitude variation within the YRD is small, and therefore the altitude impact on the observational data could be ignored. The urban center sites and the suburban sites in these cities are all located in places with no heavy industrial emission sources within 30 km. However, the urban sites are close to major roads with heavy traffic and large population aggregations. All suburban sites are nearly 30-40 km away from the urban centers and inhabited by a small population. The suburban site of SH is near the ocean, while other suburban cities from other cities are surrounded by crop fields without impact of mountains or ocean. Compared to the suburban sites, there are more artificial buildings and less green spaces in urban areas. The specific locations of all the sites are shown in Fig. 1 and were used in the model experiments. The urban sites in NJ, HZ, SH, HF are marked as U_NJ, U_HZ, U_SH, U_HF and suburban sites are represented by S_NJ, S_HZ, S_SH, S_HF.
Figure 1. Locations of the urban stations (U_NJ, U_HZ, U_SH, U_HF) and the suburban stations (S_NJ, S_HZ, S_SH, S_HZ) of Nanjing, Hangzhou, Shanghai and Hefei in Yangtze River Delta, China. The urbanization rate represents the proportion of urban population to total population.

2.2 NUMERICAL EXPERIMENTS

The Weather Research and Forecasting (WRF) model coupled with Chemistry Version 3.7 (Grell et al., 2005; Skamarock and Klemp, 2008; Skamarock, 2006) is an online modelling system and was used for this paper to investigate the influences of the Air Pollution Control Plan on UHIs. The WRF-Chem uses a non-hydrostatic dynamical core and includes emissions of gas-phase species and aerosols, gas phase chemical transformations, photolysis, gas-particle partitioning for inorganic and organic aerosol species as well as the removal of gas phase and aerosol species by wet and dry deposition.
In this study, the physics scheme was chosen to be Purdue Lin microphysics scheme (Lin et al., 1983) and the cumulus scheme was Grell-Devenyi (Grell and Dévényi, 2002). The shortwave parameterization was NOAA Goddard (Chou et al., 2001) and the longwave parameterization is RRTM (Mlawer et al., 1997). The gas-phase chemistry was based on the Carbon-Bond Mechanism version Z mechanism with 67 species and 164 reactions in a lumped structure approach that classifies organic compounds according to their internal bond types (Zaveri and Peters, 1999). The Fast-J scheme was used to derive the rates for photolytic reactions (Wild et al., 2000). The aerosol module was the Model for Simulating Aerosol Interactions and Chemistry (MOSAIC), including sulfate, methane sulfonate, nitrate, chloride, carbonate, ammonium, sodium, BC, OC, liquid water and other inorganic mass (Zaveri et al., 2008). Both biogenic and anthropogenic contributions to emissions were included. Biogenic emissions were calculated online using Guenther’s scheme (Guenther et al., 1993; Guenther et al., 1994). Anthropogenic emissions were supplied from an offline resource, based on the work of MEIC (Multi-resolution Emission Inventory for China) including the species SO2, NOx, CO, NH3, NMVOC, PM2.5, PM10, BC, OC and CO2.

The model was configured with three one-way nested domains using grid resolutions of 81 km, 27 km and 9 km. The NCEP global reanalysis dataset with a 1° × 1° resolution was used to supply initial meteorological fields and boundary conditions.

To investigate the impact of the control plan on UHI intensities, two sets of experiments were conducted for January (winter) and July (summer) 2015 in YRD. The air pollutant emissions were set as the anthropogenic emissions of 2012 in the first experiment. The second experiment used approximately 50% anthropogenic emissions of 2012 to represent the anthropogenic emissions in
2015 which were reduced by the control plan. The below paragraph will show that the 50% reduction for the pollutants is a reasonable assumption. Therefore, the differences of the UHI intensities of the two experiments quantify the effect of the control plan on the UHI.

Fig. 2(a) shows a quantitative comparison of the hourly observed and simulated PM$_{2.5}$ concentrations at the urban stations and suburban stations in NJ, HZ, SH and HF for January and July in 2015. The HF suburban site showed some missing data during July 2015. Although the simulated monthly average PM$_{2.5}$ concentrations at U_NJ and S_NJ are over predicted by approximately 10 μg m$^{-3}$, the hourly variations of all the sites are well simulated when compared to the observations of the two months with fine differences less than 3 μg m$^{-3}$. In particular, the peak values of PM$_{2.5}$ concentrations in January and July are well reproduced at all the sites. To further validate the model, the hourly simulation results of the UHI intensities in NJ, HZ, SH and HF are evaluated against in-situ observations for January and July in Fig. 2(b). The hourly variations of the UHI intensities at NJ and SH are well captured by the model in the two months. Although the model underestimates the UHI intensity values somewhat at HZ at the end of July, it still captures the hourly variations of the UHI intensities at HZ in January and July. However, the UHI intensities at HF are underestimated in January by nearly 1 K and over predicted by approximately 1.2 K in July. In conclusion, despite some discrepancies between observed and simulated results, the 50% reduced anthropogenic emissions in 2012 seems reasonable to represent the anthropogenic emissions in 2015 and the model results are credible for further analysis.
Figure 2. Comparison of observed and simulated PM$_{2.5}$ concentration and UHI intensity values of...
Nanjing, Hangzhou, Shanghai and Hefei in Yangtze River Delta, 2015. (a) Comparison of the hourly average observed and simulated PM$_{2.5}$ concentrations at the urban and suburban sites of Nanjing, Hangzhou, Shanghai and Hefei in Yangtze River Delta. (b) Comparison of the hourly average observed and simulated UHI intensities of Nanjing, Hangzhou, Shanghai and Hefei in Yangtze River Delta.

3 RESULTS

3.1 LONG-TERM ANALYSIS OF OBSERVED PM$_{2.5}$ AND UHI INTENSITY TRENDS FROM 2014 TO 2017

Fig. 3 shows a long-term analysis of observed PM$_{2.5}$ concentrations and UHI intensities data using one-hour sampling intervals. Despite some missing observational data in Fig. 3(b-d) and Fig. 3(h), Fig. 3(a-d) show a decline of PM$_{2.5}$ concentrations in the target cities of YRD, not only the annual average values but also the peak values. Of all four cities, HF always suffers the most severe pollution, but since 2014 the annual average PM$_{2.5}$ concentration reduced by 26.56 $\mu$g m$^{-3}$. NJ used to have higher PM$_{2.5}$ levels than HZ and SH in 2014 but the control plan finally made NJ, HZ and SH have similar PM$_{2.5}$ concentrations with an annual average value of around 35 $\mu$g m$^{-3}$ in 2017. The annual PM$_{2.5}$ levels in NJ, HZ, SH and HF in 2017 are approximately reduced by 48.36%, 28.25%, 29.41% and 32.5% when compared to the 2014 values, which indicates a significant improvement of air quality of China. The detailed statistic data of PM$_{2.5}$ concentrations of these four cities from 2014 to 2017 was shown in the supplementary file. Usually, the PM2.5 concentrations in the urban center were higher than that in the suburban.

In contrast to the decreased PM$_{2.5}$ pollution levels, the UHI intensity increased from 2014 to
2017 in YRD as shown in Fig. 3(e-h). As the annual average value of \( T_{UHI} \) would balance the characteristics of UHI phenomenon and may not reflect the inter-annual variability well, we define the annual frequency of UHI as the proportion of \( T_{UHI} \) greater than zero as a metric for the UHI intensities in YRD. HF had the smallest UHI frequency with highest PM\(_{2.5}\) level in 2014 of the four cities, but the UHI frequency in HF increased rapidly to 17.19% with 23.4% decreased PM\(_{2.5}\) concentration in 2015. The UHI frequency in NJ strengthened much more than that in SH and HZ every year with the higher decrease of PM\(_{2.5}\) concentrations. The risings of the annual UHI frequencies in Fig. 3(e-h) appeared slower in 2016 and 2017 when compared to that in 2015, which is consistent with the falling rates of PM\(_{2.5}\) level in Fig. 3(a-d). However, the UHI intensities are also dependent on other factors such as landscape and surface albedo; thus we cannot expect that the UHI intensities of NJ, SH, HZ and HF respond linearly to reductions in PM\(_{2.5}\) but the mechanisms are similar in all four locations. We hypothesize that the Air Pollution Control Plan causes the increase in UHI intensities in YRD as a response to PM\(_{2.5}\) levels. To investigate this hypothesis, we will compare the observed UHI intensities under different PM\(_{2.5}\) levels. At the same time, we will use the WRF-Chem model to do numerical experiments and further analyze the effect of PM\(_{2.5}\) on UHI intensities.
Figure 3. Time series of PM$_{2.5}$ concentration and urban heat island intensity values from 2014 to 2017 in in Yangtze River Delta. Time series of PM$_{2.5}$ concentration in (a) Nanjing; (b) Hangzhou; (c) Shanghai; (d) Hefei. Time series of Urban heat island intensity in (e) Nanjing; (f) Hangzhou; (g) Shanghai; (h) Hefei.

3.2 OBSERVED PM$_{2.5}$ EFFECTS ON UHIS
Figure 4. Observed diurnal variations of UHI intensities for different PM$_{2.5}$ levels in YRD, 2014-2017. (a-1) 2014, NJ; (a-2) 2015, NJ; (a-3) 2016, NJ; (a-4) 2017, NJ. (b-1) 2014, HZ; (b-2) 2015, HZ; (b-3) 2016, HZ; (b-4) 2017, HZ.
Figure 5. Observed diurnal variations of UHI intensities for different PM$_{2.5}$ levels in YRD, 2014-2017. (a-1) 2014, SH; (a-2) 2015, SH; (a-3) 2016, SH; (a-4) 2017, SH. (b-1) 2014, HF; (b-2) 2015,
To further investigate the hypothesis, we classified the hourly values of the UHI intensities into three groups according to the observed PM$_{2.5}$ concentrations in the four urban centers, representing light (PM$_{2.5}$ concentrations less than 35 $\mu$g m$^{-3}$), medium (PM$_{2.5}$ concentrations greater than or equal to 35 $\mu$g m$^{-3}$ and less than or equal to 75 $\mu$g m$^{-3}$) and heavy PM$_{2.5}$ levels (PM$_{2.5}$ concentrations greater than 75 $\mu$g m$^{-3}$). Since the concentrations of PM$_{2.5}$ decreased with the pollution control plan, we do not have any data points in the category “heavy PM$_{2.5}$ levels” in HZ and SH for the year 2017 (Fig. 4b-4 and 5a-4). In Fig. 4 and 5, negative $T_{UHI}$ values represent that the suburban region is warmer than the urban region and the positive values represent that the urban region is warmer.

In Fig. 4 and 5, the diurnal cycles of $T_{UHI}$ are compared for the three PM$_{2.5}$ levels defined above. For the same PM$_{2.5}$ levels, the $T_{UHI}$ values vary between cities, with higher positive values in SH and HF compared to NJ and HZ. For the light, medium and heavy PM$_{2.5}$ levels in HZ as well as for the medium and heavy PM$_{2.5}$ levels in NJ and SH, we found similar characteristics as maximum values occur at nights (1 K – 1.5 K in HZ, 0.5 K – 0.8 K in NJ and 0.5K – 1.5 K in SH, respectively) and minimum values occur during the afternoons (-0.5 K – 0.5 K in HZ, -0.1 K – 0.3 K in NJ and 0 K – 0.5 K in SH, respectively). The peak values at night results from the smaller wind speed and the inversion layer, they work together to inhibit the turbulent transport of the near-surface heat in the urban center to the upper air.

The $T_{UHI}$ values under light PM$_{2.5}$ levels in NJ have small diurnal variation with values of
less than 0.5 K. At SH, $T_{UHI}$ is lowest in the mornings (0 K) with values of about 0.5 K in later hours. HF is different from NJ, HZ and SH in that it shows the maximum $T_{UHI}$ values occurring in the afternoons (1 K – 1.5 K, respectively) and the minimum values occur before dawn (-1 K – 0 K, respectively) under light, medium and heavy PM$_{2.5}$ levels. This regulation may come from the terrace topography of HF when compared to other three cities, which need further investigation.

For any given year, as the PM$_{2.5}$ levels decrease from heavy to light, the UHI intensities increase during the daytime and decrease at night-time in the four cities. The $T_{UHI}$ values for light PM$_{2.5}$ levels in SH and HF in 2014 do not follow this pattern for some of the hours. This can be explained by only a few data points entering the calculation for $T_{UHI}$, so the light levels in Fig. 5a-1 and 5b-1 are not representative. To compare the trend in $T_{UHI}$ under different PM$_{2.5}$ levels, we averaged the daytime values and the night-time values separately. We define 7am-18pm as daytime and 18pm-7am as night-time. From 2014 to 2017, the averaged daytime UHI intensities in NJ strengthened by 0.2 K–0.6 K, by 0.2K–0.5 K in HZ, by 0.3 K–1 K in SH, and by 0.5 K–1 K in HF when the PM$_{2.5}$ levels varied from heavy to light level. However, the night-time UHI intensities are reduced by 0.5 K–0.8 K in NJ, 0.2 K–0.5 K in HZ, 0.3 K–1 K in SH and 0.5 K–1 K in HF at the same time. The impact of PM$_{2.5}$ levels on UHI intensities vary between different cities but the same pattern can be observed as the UHI intensities was strengthened in the daytime and reduced at night from 2014 to 2017 when the PM$_{2.5}$ level became lighter, due to the implementation of the control plan. To distinguish the $T_{UHI}$ variation due to the PM$_{2.5}$ concentrations but not from the ambient meteorological conditions, we taken different seasons into consideration. The impact of PM$_{2.5}$ levels on UHI intensities shows the consistent regulation in different seasons from 2014 to 2017.
In all seasons, the UHI intensities were strengthened in the daytime and reduced at night when the PM$_{2.5}$ levels changed from heavy to light level. The detailed figures are shown in the supplementary file. The correlations between the $T_{UHI}$ values and the corresponding PM$_{2.5}$ differences of the urban and suburban sites ($\Delta$PM$_{2.5}$) of NJ, HZ, SH and HF from 2014 to 2017 are shown in Fig. 6. The PM$_{2.5}$ values range from 0 to 60. Negative correlations between the UHI intensity and $\Delta$PM$_{2.5}$ were found for all the four cities for the daytime: as $\Delta$PM$_{2.5}$ increased, the UHI intensity tended to decrease in the daytime. Oppositely, positive correlations between these two quantities were found during the night-time: as $\Delta$PM$_{2.5}$ increased, the UHI intensity tended to increase. The linear regression coefficients ($r$) of each panel in Fig. 6 are given in Table 1 as -0.148, -0.102, -0.103 and -0.121 in the daytime and 0.083, 0.107, 0.128 and 0.098 in the night-time of NJ, HZ, SH and HF. A higher positive value of $r$ represents the stronger positive correlation and vice versa. The results from separating the data in day and night groups confirm our hypothesis that the air pollution control could not only cause increases of the UHI intensities in the daytime but also result in decreases of the UHI intensities during the night-time. We name this the ‘seesaw effect’ because the air pollution control plan impacts the UHI intensities in the daytime and night-time in opposite ways: increases of UHI intensities in the daytime occur alongside reductions of the UHI intensities during the night-time.
Figure 6. Correlations between the observed UHI intensities and PM$_{2.5}$ concentration differences of Nanjing, Hangzhou, Shanghai and Hefei in daytime and night-time, 2014-2017. (a) Daytime, Nanjing; (b) Night-time, Nanjing; (c) Daytime, Hangzhou; (d) Night-time, Hangzhou; (e) Daytime, Shanghai; (f) Night-time, Shanghai; (g) Daytime, Hefei; (h) Night-time, Hefei.
Shanghai; (f) Night-time, Shanghai; (g) Daytime, Hefei; (h) Night-time, Hefei.

Table 1. Linear correlation coefficients of each panel in figure 6.

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3.3 SIMULATED EFFECTS ON SURFACE TEMPERATURE WITH THE AIR POLLUTION CONTROL PLAN

As described in the methodology section, WRF-Chem simulations were conducted to investigate the effects of the control plan on the surface temperature in YRD. Two experiments, one with 2012 anthropogenic emissions and one with 50% reduced 2012 anthropogenic emissions (representing anthropogenic emissions in 2015), were carried out. The differences of the surface PM$_{2.5}$ concentrations, the downward shortwave radiation ($\Delta SW$) at the surface, the TOA outgoing longwave radiations ($\Delta LW$) and the surface temperatures ($\Delta T$) were taken to assess the role of the Air Pollution Control Plan on the surface temperature. As PM$_{2.5}$ has negative surface radiative forcing and increases cloud condensation nuclei, the $\Delta SW$, $\Delta LW$ and $\Delta T$ are expected to be greater than 0 with lower PM$_{2.5}$ loadings (Im et al., 2012; Susskind and Molnar, 2011).

The horizontal distribution of the monthly averaged surface PM$_{2.5}$ concentrations differences caused by the pollution control plan over the YRD from the output of the lowest model layer is
shown in Fig. 7(a) and 7(b). The control plan reduced the PM$_{2.5}$ concentrations of the YRD by 90 μg m$^{-3}$ to 120 μg m$^{-3}$ in January, and 40 μg m$^{-3}$ to 70 μg m$^{-3}$ in July, respectively. A more unstable atmosphere during the summer leads to the increased amount of precipitation and better ventilation conditions, resulting in increased surface PM$_{2.5}$ removal by wet deposition (Wu et al., 2017). Due to that, PM$_{2.5}$ concentrations in summer are always lower than winter.

Due to these factors, the PM$_{2.5}$ concentration levels are different for the 2012 base case in January and July, leading to the differences in the monthly averaged surface PM$_{2.5}$ concentrations for January and July in 2015 after the control plan. However, the distribution patterns of PM$_{2.5}$ concentration differences are similar in summer and winter in that the largest decreases of PM$_{2.5}$ are found in the urban centers of NJ, HZ, SH and HF as these are the areas with the highest concentrations for fine particles (MEE, 2013; MEE, 2014) compared to the suburban regions.

The $\Delta SW$ and $\Delta LW$ caused by the decreases of PM$_{2.5}$ are not only dependent on the reduction value of PM$_{2.5}$ but also on the amount of energy that the earth received from the sun. As the earth received more solar radiation from the sun in July than the January, the $\Delta SW$ and $\Delta LW$ are higher in July even though the PM$_{2.5}$ change is lower for that month (Fig. 7(c), 7(d), 7(e) and 7(f)). During the daytime, the pollution control plan enhanced the surface downward solar radiation (SW) in YRD ranging from 4-16 W/m$^2$ in January and 8-36 W/m$^2$ in July by reducing PM$_{2.5}$ levels, leading to the increases of surface temperature (Fig. 7(g) and 7(h)). The TOA outgoing longwave radiation (LW) is the energy radiating from the Earth to Space and causes radiative cooling of the atmosphere. Increased LW cooling results from the decreases of PM$_{2.5}$ and causes a decrease of surface temperature in the night-time, which will be discussed in the next section.
The monthly averaged surface temperature change ($\Delta T$) caused by the air pollution plan (Fig. 7g and 7h) results from the changes of SW and LW and $\Delta SW$ plays the dominant role, which means that Fig. 7g and 7h represent the daytime effect of the pollution control plan. Owing to the seasonal variation of the PM$_{2.5}$ differences and $\Delta SW$, $\Delta T$ is generally higher in July and lower in January over the YRD. However, the atmosphere is a system with complex feedbacks. For example, the changes in surface temperature by PM$_{2.5}$ will change the moisture transport and result in precipitation feedbacks, which in turn affect the surface temperature. Therefore the horizontal distribution of $\Delta T$ cannot be expected to always look similar to the distribution of the PM$_{2.5}$ differences, but the $\Delta T$ gradient around the PM$_{2.5}$ sources can be found in Fig. 7g-h and 7a-b. We need to compare the $\Delta T$ of the urban areas to the $\Delta T$ of the suburban areas in the four cities to determine the impact of the pollution control plan on the UHI. Fig. 7g and 7h show the same results that the $\Delta T$ values in urban centers of NJ, HZ, SH and HF (nearly 0.32 K) are higher than that in the suburban areas (nearly 0.16 K), indicating the strengthened UHI intensity caused by the control plan.
Figure 7. Monthly averaged surface PM$_{2.5}$ concentrations change, surface downward shortwave radiation change $\Delta SW$, TOA outgoing longwave radiations change $\Delta LW$ and surface temperature.
change $\Delta T$ at a 2-m height due to the air pollution control plan in YRD, 2015. (a) Surface PM$_{2.5}$ concentrations change in January; (b) Surface PM$_{2.5}$ concentrations change in July; (c) $\Delta SW$ in January; (d) $\Delta SW$ in July; (e) $\Delta LW$ in January; (f) $\Delta LW$ in July; (g) $\Delta T$ in January; (h) $\Delta T$ in July.

### 3.4 UHI INTENSITY SEESAW BY THE AIR POLLUTION CONTROL PLAN

![Figure 8](image.png)

**Figure 8.** Monthly average of the diurnal cycles of the simulated changes in UHI intensities ($\Delta T_{UHI}$) due to air pollution control in Yangtze River Delta, 2015. (a) $\Delta T_{UHI}$ of Nanjing in January and (b) in July. (c) $\Delta T_{UHI}$ of Hangzhou in January and (d) in July. (e) $\Delta T_{UHI}$ of Shanghai in January and (f) in July. (g) $\Delta T_{UHI}$ of Hefei in January and (h) in July.
According to the observational results, the UHI intensity is strengthened during the day and weakened in the night as the PM$_{2.5}$ concentrations decrease. From the last section, the inhomogeneous warming effect on the surface temperature can indeed be found across the YRD (Fig. 7(g-h)). But the daytime effects dominate over the nighttime effects and therefore the nighttime effects are not visible in the monthly averages of UHI intensities. Next, we quantify the diurnal variations of $\Delta T_{UHI}$ caused by the presence of the pollution control plan, shown in Fig. 8.

During the daytime, the surface temperature was increased due to the increased SW caused by the decreased PM$_{2.5}$ levels. Since the reduction of PM$_{2.5}$ loadings in the urban center is consistently larger than that in the suburban areas of the four cities, the $\Delta T$ was larger in the urban centers, which explains the strengthened UHI intensity when the pollution control plan was included in the simulations. Thus $\Delta T_{UHI}$ values of the target cities in YRD are always greater than 0 during the daytime and vary with locations. The negative values of $\Delta T_{UHI}$ during the night-time were found as well, which is consistent with the observed analysis in Fig. 4, 5 and 6. The reduction of PM$_{2.5}$ levels due to the control plan increased the LW radiation (Fig. 7e-f), leading to the decreased UHI intensity in the night-time. Cao et al. (2016) confirmed that the high levels of PM$_{2.5}$ would enhance the UHI intensities over China, which is consistent with us.

The magnitude of the $\Delta T_{UHI}$ was larger in July than in January. The seasonal variations of $\Delta T_{UHI}$ depend on both the available solar radiation and the differences of PM$_{2.5}$ concentrations. Although the PM$_{2.5}$ levels differences in July is smaller as we have discussed above, the $\Delta SW$ and $\Delta LW$ both have higher values in July. As a result, $\Delta T_{UHI}$ shows a higher magnitude in July than in
January in all the four cities, which means the ‘seesaw effect’ of the control plan is more prominent in summer. This effect on UHI intensities also varies from the locations. In January, the absolute values of $\Delta T_{UHI}$ is always lowest in HF (0.02 K–0.05 K) but highest in SH (0.1 K–0.12 K), which means that the control plan impacts SH most but HF least. HZ has the largest absolute values of $\Delta T_{UHI}$ in July (0.16 K–0.18 K) and SH has slightly smaller absolute $\Delta T_{UHI}$ values (0.12–0.16 K), and the control plan still affected HF least (0.1 K, respectively).

4. DISCUSSION

Our study reveals that the air pollution control plan in YRD reduced PM$_{2.5}$ levels by nearly 30 % from 2014 to 2017 and strengthened the UHI intensities during the daytime, while reducing UHI intensities during the night-time. Based on the observational data, the UHI intensity was increased by up to 1 K in the daytime and reduced by up to 1 K at the night-time under light PM$_{2.5}$ levels. We named this phenomenon the ‘seesaw effect’ in this paper. According to our simulations, the reduction of PM$_{2.5}$ loadings increased the daytime surface downward shortwave radiation by up to 16 W/m$^2$ in January and 36 W/m$^2$ in July, leading to the warmer surface temperature in YRD. During the night-time, TOA outgoing longwave radiation also increased with the reduced PM$_{2.5}$, resulting in the cooler surface temperature. The simulated effects of the control plan on PM$_{2.5}$ concentrations were more evident in the urban centers compared to the suburban areas for all four studied cities in January and July. The inhomogeneous decreases of PM$_{2.5}$ levels cause uneven impacts on surface temperatures of the urban center and the suburban area, thus changing UHI intensities. The simulated $\Delta SW$ and $\Delta LW$ in YRD is larger in July than in January, which is consistent with those of $\Delta T_{UHI}$, where the UHI intensity is affected less in January but more in July.
Comparing the simulated $\Delta T_{\text{UHI}}$ of NJ, HZ, SH, HF, we conclude that SH and HZ are affected most and HF is affected least by the control plan.

The PM$_{2.5}$ levels and the UHI intensities are significant reference signals of the urban environment. We showed that the reduction of PM$_{2.5}$ levels intensified the UHI intensities during the daytime and declined those at night-time. Thus, the air pollution in the last years masked the UHI effects, and contamination levels need to be considered when analyzing UHI intensities of different cities. In the last decades, heavy air pollution in China may mask the UHI phenomenon and other problems of ‘city disease’. The conduction of the air pollution control plan would expose these problems of urban climate when ease the pollution. It would be significant to take measurements like establishing the urban ventilation corridors to ease UHI and other city problems at the same time.

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