How Does PM$_{2.5}$ Impact the Urban Vertical Temperature Structure? A Case Study in Nanjing

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ABSTRACT

PM$_{2.5}$ impacts the atmospheric temperature structure through scattering or absorbing solar radiation, whose concentration and composition can affect the impact. This study calculated the effect of PM$_{2.5}$ on the temperature structures in the urban centre and the suburbs of Nanjing, as well as their differences. The results show that the optical parameters, atmospheric heating rate, radiative forcing, and temperature are all impacted by the concentration and composition of PM$_{2.5}$. The uneven distribution of PM$_{2.5}$ influences the differences in those factors between the urban centre and suburbs. In spring, summer, autumn, and winter, surface temperatures in the urban centre were approximately 283 K, 285 K, 305 K, and 277 K, while those in the suburbs were approximately 282 K, 283 K, 304 K, and 274 K. The urban heat island intensity has been reduced by 0.1–0.4 K due to the presence of PM$_{2.5}$ in Nanjing. Due to the black carbon component’s warming effect on the top of the boundary layer, the impact of PM$_{2.5}$ on the urban heat island intensity profile drops quickly at the 0.75–1.25 km. PM$_{2.5}$ may mask the “warm city” problem and have a more complex impact on the urban climate.

Keywords: PM$_{2.5}$, Urban heat island, Box model, Radiative forcing, Fine particulate matter

1 INTRODUCTION

An urban heat island (UHI) is a thermal environment that occurs in the urban centre compared to its surroundings (Memon et al., 2008). The UHI intensity can be defined as the temperature difference between urban and rural areas, which is most prominently present during the nighttime (Yang et al., 2020). The UHI phenomenon can be affected by numerous factors like albedo, anthropogenic heat, vegetation cover, wind speed, cloud cover, and air pollutants (Huang et al., 2005; Kim and Baik, 2005; Oke, 1982; Pongracz et al., 2006). A combination of these factors alters the exchange of the solar radiation reaching the surface and the outgoing radiation from the surface at the urban centre, thus influencing a rise in local temperature and finally resulting in the UHI (Tam et al., 2015).

As the primary air pollutant in China, fine particle matter (PM$_{2.5}$) can affect the surface energy balance and thereby change the temperature. It is believed that the abundant air pollutants over urban centre can absorb the solar radiation and inhibit a corresponding radiative surface cooling
effect, which is responsible for the change in UHI intensity (Memon et al., 2008). The radiation forcing caused by PM$_{2.5}$ in the most urbanised areas of China can be up to $-30$ W m$^{-2}$ during the daytime (Kuhlmann and Quaas, 2010; Xia et al., 2007). Zhuang et al. (2014) reported that the radiation forcing of urban total and absorbing aerosols on the top of the atmosphere was approximately $-6.9$ W m$^{-2}$ and $-21.3$ W m$^{-2}$, respectively; at the surface in Nanjing, the radiation forcing of absorbing aerosols is $+4.5$ W m$^{-2}$ on the top and $-7.9$ W m$^{-2}$ at the surface, which means the absorbing aerosols can heat the top of the atmosphere and cool the bottom. The radiation effect of PM$_{2.5}$ may reduce the surface temperature up to 2 K (López-Romero et al., 2021; Lu et al., 2020; Ma et al., 2023).

The inhomogeneous distribution of fine particles could alter temperatures within the urban heat island (Wu et al., 2017, 2021, 2019; Yang et al., 2020). Due to industrial development, intensive human activities, and high levels of traffic, the concentration of PM$_{2.5}$ is higher in the urban centre than in the suburbs (Zhang et al., 2022; Zhao et al., 2009). The significant differences between urban and suburban underlying surface characteristics as well as the compositions and concentrations of PM$_{2.5}$ and the radiative forcing caused by PM$_{2.5}$ lead to the different changes in urban and suburban air temperature (Qu et al., 2023; Tran and Moelders, 2011; Wang et al., 2018), thus making the urban centre cooler and leading to a decrease in the UHI intensity (Wu et al., 2021). The total vertical structure of atmospheric temperature can be impacted by PM$_{2.5}$ as the particles could change the atmospheric heating rate, which is related to the compositions and concentrations of fine particles (Wu et al., 2023). The effect of PM$_{2.5}$ on the UHI intensity differs radically between day and night-time. The UHI intensity would be increased during the day and decreased at night as the PM$_{2.5}$ could reduce the solar radiation by day and reflect the emitted longwave radiation from the surface at night (Cao et al., 2016; Jonsson et al., 2009; Wu et al., 2021).

Both concentration and variations in chemical composition contribute to UHI intensity difference between urban and suburban areas. The urban centre and the suburbs have different PM$_{2.5}$ compositions (Li et al., 2007). The SSA of aerosols in the urban centre of Beijing was smaller than in the suburbs of Beijing, measuring 0.88, as calculated by Yan et al. (2007). These consistent conclusions confirmed that the urban centre would have more absorbing aerosols. The distribution of PM$_{2.5}$’s composition in China shows that levels of the scattering aerosols in southern China are higher than in northern China (Garland et al., 2008; Wu et al., 2009). Compared to the SSA value of 0.90 in the Taihu region (Xia et al., 2007), it can be concluded that the industrially developed, high-traffic area emitted more absorbing aerosols, which were represented by black carbon aerosol (Liu et al., 2019; Ramachandran et al., 2012; Zhuang et al., 2014, 2016). Absorbing particles of PM$_{2.5}$ can reduce the surface temperature (Satheesh and Ramanathan, 2000) but warm the top of the atmosphere (Podgorny and Ramanathan, 2001; Ramachandran, 2005). Alternatively, the scattering aerosols reduce the surface temperature (Iizuka et al., 2012). Although the different compositions all reduce the UHI intensity during daylight, their reduction ability is different. Our previous work revealed that a unit of absorbing PM$_{2.5}$ has a greater radiative forcing effect and impact on the UHI than a unit concentration of scattering particles (Wu et al., 2023, 2021).

Observational analysis and numerical simulations indicated that the UHI intensity experienced reversed effects of PM$_{2.5}$ during the day and night-time (Cao et al., 2016; Wu et al., 2014, 2019). The relationship between the UHIs and PM$_{2.5}$ has been determined in these previous works by three-dimensional numerical models (Wu et al., 2009; Kuhlmann and Quaas, 2010; Zhuang et al., 2014; Yang et al., 2020), which is designed to simulate the real atmosphere including complex feedback among many factors. The previous works cannot definitely separate the impact of PM$_{2.5}$ on UHIs, so the sensitive experiments have been conducted using a box model (Wu et al., 2023). However, calculations did not incorporate the specific chemical composition of a city as part of a case study to investigate the seasonal variation of PM$_{2.5}$’s impact on UHIs. An atmospheric chemistry model named Particle Monte Carlo-Model for Simulating Aerosol Interactions and Chemistry (PartMC-MOSAIC) coupled with the Rapid Radiative Transfer Model (RRTM) and the surface energy balance equation was used as a box model to investigate the seasonal variations.

The experiments were conducted in January, April, August, and October in Nanjing. Nanjing located in the Yangtze River Delta is one of the cities with the highest urbanization rate in China, the calculated results are representative and can represent the general situation of urban agglomerations in eastern China. As PM$_{2.5}$ is designated as the target aerosol in the box model, aerosol-related
terms, including AOD, SSA, and radiative forcing, subsequently refer to the results of PM$_{2.5}$. The UHI intensity is represented as $T_{UHI}$ and the UHI intensity change is represented by $\Delta T_{UHI}$.

## 2 METHODS

In this study, a one-dimensional aerosol radiation convection model has been developed based on an atmospheric chemistry model named PartMC-MOSAIC coupled with a widely used atmospheric radiation transfer model called RRTM and the surface energy equation. This convection model divides the spectrum according to the particle size, thus focusing on single particles, which improves the ability to calculate aerosol chemical characteristics, aerosol radiative forcing effects, atmospheric heating rates, and temperatures (Wu et al., 2023).

PartMC-MOSAIC is the Optics Module of the box model to calculate the optical parameters of aerosols by using the MOSAIC mechanism. The output of this module is the optical parameters of aerosols, such as extinction coefficient, scattering coefficient, absorption coefficient, SSA, and asymmetry. All these parameters, as well as the input heights, are used in the next Radiation Transfer Module based on the Rapid Radiative Transfer Model (RRTM) to calculate the impact of PM$_{2.5}$ on aerosol radiation values and atmospheric heating rates. The results of the Radiation Transfer Module are the radiative forcing and the heating rate which represents the impact of the PM$_{2.5}$ on the solar radiation and is the input parameter of the next model. The last module is the surface energy equation, which can calculate the surface temperature taking into account the surface parameters including albedo, roughness, and Bowen ratio. The final results of the box model are the atmospheric heating rate and atmospheric temperature at different heights. The development of the model is shown in Fig. 1. More detailed information can be found in our previous study (Wu et al., 2023).

The construction of cities could reduce vegetation coverage, surface humidity, and heat exchange between the surface and the atmosphere, leading to a decrease in surface albedo but an increase in Bowen ratio and roughness (Baldocchi et al., 2000; Wilson and Baldocchi, 2000). The anthropogenic heat in the urban centre is also strengthened due to industrial and commercial activities. According to the previous studies of these surface parameters (Kafanda et al., 1980; Wu et al., 2023), the values used in this study are shown in Table 1.

![One-dimensional aerosol radiation convection model](image)

**Fig. 1.** Development of one-dimensional aerosol radiation convection model.
3 RESULTS AND DISCUSSION

3.1 The Compositions and Concentrations of Fine Particles

The observation of PM$_{2.5}$ in Nanjing was conducted at the urban site in Gulou (118.80°E, 32.06°S) and at the suburban site in Xianlin (118.80°E, 32.06°S). The observation lasts one year but is not completed in a calendar year. The data was collected in January, April, and August 2015 and October 2014 to represent the seasonal variations of winter, spring, summer, and autumn. The total amount of the observation data is 738 filters samples. More details of this observation campaign and the datasets can be found in our published work (Chen et al., 2017).

The concentration of major components of PM$_{2.5}$ in Nanjing is shown in Fig. 2, and the proportion of each component of fine particulate matter in urban and suburban areas is shown in Fig. 3. The concentrations of PM$_{2.5}$ in the urban centre were 99.42 µg m$^{-3}$ in January, 45.62 µg m$^{-3}$ in April, 32.61 µg m$^{-3}$ in August, and 68.01 µg m$^{-3}$ in October. Compared to the PM$_{2.5}$ concentration in the suburbs (97.41 µg m$^{-3}$ in January, 43.2 µg m$^{-3}$ in April, 30.54 µg m$^{-3}$ in August, and 65.7 µg m$^{-3}$ in October), the urban centre has more fine particles. The concentration in urban and suburban areas is both highest in winter (approximately 98–99 µg m$^{-3}$) and lowest in summer (approximately 30–32 µg m$^{-3}$). The concentration of PM$_{2.5}$ has decreased in comparison with the previous observation results in Nanjing shown in Table 2, which is consistent with the implementation of the Air Pollution Prevention and Control Action Plan in China (Cai et al., 2017; Geng et al., 2019). The PM$_{2.5}$ observation conducted by Wu et al. (2016) in the northern suburbs of Nanjing in 2014 is approximately 20–40 µg m$^{-3}$ higher than the PM$_{2.5}$ concentration in our study during spring, summer, and autumn. This is mainly because of the location of the suburban site. In our study, the suburban site is in the east of Nanjing, which is further away from the chemical industry compared with the northern suburbs of Nanjing (Wu et al., 2017). The concentrations of nitrate aerosol, sulphate, black carbon, and organic carbon in the PM$_{2.5}$ were consistent with the seasonal

![Fig. 2. The concentrations of main PM$_{2.5}$ compositions in Nanjing from 2014–2015.](image-url)
The heavy PM$_{2.5}$ pollution that happened in winter is related to the increase of coal burning emissions and stable atmospheric stratification, while the strong atmospheric convection, abundant precipitation, and high temperature in summer lower the PM$_{2.5}$ level (Cao et al., 2012).

Fig. 3. The proportions of PM$_{2.5}$ compositions in Nanjing during 2014–2015.
Table 2. Summary of PM$_{2.5}$ concentration observations in Nanjing.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Season</th>
<th>PM$_{2.5}$ concentration ($\mu$g m$^{-3}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban centre</td>
<td>2004</td>
<td>Summer</td>
<td>69.1</td>
<td>Huang et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>2005</td>
<td>Winter</td>
<td>139.5</td>
<td></td>
</tr>
<tr>
<td>Urban centre</td>
<td>2013</td>
<td>Summer</td>
<td>67.44</td>
<td>Yuan et al. (2014)</td>
</tr>
<tr>
<td>Suburban</td>
<td>2014</td>
<td>Spring</td>
<td>83.1</td>
<td>Wu et al. (2016)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Summer</td>
<td>80.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Autumn</td>
<td>84.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Winter</td>
<td>91.0</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3 shows the main compositions of PM$_{2.5}$ and their concentrations. In Nanjing, the main compositions are nitrate (NO$_3^-$), sulphate (SO$_4^{2-}$), organic carbon (OC) and elemental carbon (EC). It has the same seasonal variation in the urban and suburban as the highest proportions of SO$_4^{2-}$ and NO$_3^-$ are in summer and they are lowest in winter. In winter, the proportion of BC increases due to the stable atmosphere and less precipitation (Li et al., 2015; Kozlov et al., 2009). Coal soot contributes more to fine particles in winter as well as fireworks have little effect on the formation of sulphate particles, but BC are significantly increased by this process during the Spring Festival (Wang et al., 2014). Conversely, the photochemical conversion rate of SO$_2$ is stronger in summer due to the characteristics of intense solar radiation and high temperature (Baltensperger et al., 2002; Kim et al., 2016). Thus, it can be found from the seasonal variations that the NO$_3^-$ and SO$_4^{2-}$ dominate in the summer, while the OC and BC are dominant in the winter.

Throughout the year, the proportion of OC and EC in urban centre (20.43–27.84%) is always higher than that in suburban (18.32–24.51%) as the contribution of coal burning and smelting dust to fine particles is greater in urban aerosol sources than in suburban (Fan et al., 2005). In general, the concentration of PM$_{2.5}$ in the urban centre of Nanjing is higher than that in the suburban area, as well as the proportion of BC. The difference in the compositions of PM$_{2.5}$ lead to differences in radiative forcing effects and further affect the change of surface air temperature between the urban and suburbs.

3.2 Optical Properties and Radiative Forcings of PM$_{2.5}$

Here we use the concentrations of main PM$_{2.5}$ components displayed in Fig. 2 to calculate the optical parameters in urban and suburban of Nanjing, as shown in Fig. 4. Fig. 4(a) shows that the asymmetry values of urban PM$_{2.5}$ is larger in winter (approximately 0.71) and smaller in spring, summer and autumn. As we have mentioned in our previous work, the asymmetry represents the forward scattering ability of PM$_{2.5}$, which is mainly affected by the compositions of fine particles (Wu et al., 2023). The asymmetry would be bigger with higher scattering compositions. Thus, the asymmetry value of suburban PM$_{2.5}$ is larger in summer (approximately 0.72) and smaller in spring and autumn and winter due to the scattering compositions is higher in summer. The difference in asymmetry values between the urban centre and suburban is mainly manifested in summer, and the values are close to 0.7 in other seasons. The evidence shows that the forward scattering ability of suburban PM$_{2.5}$ is stronger than that of urban PM$_{2.5}$ in summer, that is, the backward scattering ability is weaker, also the extinction effect (Zhang and Shi, 2002). The single scattering albedo (SSA) in Fig. 4(b) showed a similar seasonal variation in the suburban as the maximum value was in summer (approximately 0.95–0.97) and the minimum value was in winter (0.79–0.82), which was consistent with the seasonal variation of the proportion of scattering compositions (NO$_3^-$, SO$_4^{2-}$) in Fig. 3. Actually, the SSA values is positive with the proportion of the scattering compositions as the hygroscopic growth of the scattering compositions increases the particle size (Wu et al., 2023).

Fig. 4(c) showed the seasonal variation of PM$_{2.5}$'s optical thickness at 550 nm in the urban centre and suburbs of Nanjing. There was almost no difference between the urban centre and suburban area in autumn and winter as the AOD values were approaching 0.5, which is close to the AOD value (0.5183) measured by Huang et al. (2009) at the same suburban site in autumn. In spring, the AOD value was larger in urban centre (approximately 0.4) but smaller in suburban (approximately 0.2). Oppositely, it is larger in the suburban (approximately 0.8) but smaller in the
urban centre (approximately 0.6) in summer. The AOD values in urban centre and suburban showed similar seasonal variations. The values were at their maximum in summer and minimum in spring. The higher humidity in summer lead to the stronger hygroscopic growth of nitrate and sulphate compositions and enhanced the extinction capacity, resulting in the increase of AOD. Meanwhile, the absorbing compositions have stronger extinction ability, which make the AOD values increased (Wu et al., 2023). Nitrate and sulphate PM$_{2.5}$ occupy a larger proportion in suburban than in urban centre, so the AOD value in suburban is larger than the urban centre. Wang et al. (2016) came to a similar conclusion by using Lidar to observe the AOD value in Beijing, which reached approximately 0.699 in summer.

Fig. 5 shows the vertical profiles of PM$_{2.5}$'s radiative forcing effects in Nanjing during different seasons. The PM$_{2.5}$'s radiative forcing effects in the urban centre and suburban are both larger in autumn and winter (approximately –7 W m$^{-2}$ to –9 W m$^{-2}$) than in spring and summer (approximately –4 W m$^{-2}$ to –6 W m$^{-2}$). The wet removal rate is larger in summer, which has an impact on the radiative forcing effects. Gao et al. (2004) reported that the summer radiative forcing of SO$_4^{2-}$ in east China was approximately three times larger than that in winter. With the increase in elevation, the presence of OC and EC can generate positive radiative forcing effects. Above 500 m height, the positive radiative forcing is lower in winter (approximately 3 W m$^{-2}$) and higher in autumn (approximately 5–6 W m$^{-2}$). Comparing Figs. 5(a) and 5(b), the radiative forcing effect caused by PM$_{2.5}$ is stronger in the urban centre than in the suburban area, so less solar radiation reached the urban surface. More absorbing compositions and higher concentrations of PM$_{2.5}$ in the urban centre lead to this result and the details of the relationship between the optical parameters as well as radiative forcings with the compositions of PM$_{2.5}$ can be found in our previous work (Wu et al., 2023). However, the positive radiative forcing effects in the top of the boundary layer were larger in the urban centre than the suburbs. It was revealed that the cooling effect of PM$_{2.5}$ on the surface temperature in the urban centre was stronger than the suburbs, as well as the heating effect at the upper boundary layer due to the difference in PM$_{2.5}$'s concentration and composition. As the temperature of the urban heat island altered, the temperature differential between the urban centre and the suburbs also changed.
3.3 The Atmospheric Heating Rate

To explore the impact of PM$_{2.5}$ on the atmospheric heating rates, we conducted a base experiment without the presence of PM$_{2.5}$ and the results are shown in Fig. 6. Fig. 6(a) shows the atmospheric heating rate of Nanjing in different seasons according to the surface parameters in Table 2. Under the clean atmosphere, the atmospheric heating rates in the urban centre are always higher than those of the suburban at different altitudes, and the difference between the centre and the suburban is larger below 1.75 km, indicating that the influence of underlying surface parameters on the atmospheric heating rate is mainly concentrated below the boundary layer (Zheng et al., 2006). The atmospheric heating rates in the urban centre are 2.8–3.6 K Day$^{-1}$, 2.8–3.7 K Day$^{-1}$, 2.8–3.6 K Day$^{-1}$, and 2.8–3.3 K Day$^{-1}$, respectively, in spring, summer, autumn and winter, while the atmospheric heating rates in the suburban area are approximately 2.8–3.4 K Day$^{-1}$, 2.8–3.5 K Day$^{-1}$, 2.8–3.3 K Day$^{-1}$, and 2.8–3.2 K Day$^{-1}$, respectively. The atmospheric heating rates of Nanjing were lowest in winter and highest in summer. Especially, the atmospheric heating rate of suburban in August is very close to that of urban centre in October.

Fig. 6(b) shows the atmospheric heating rates in different seasons under the real atmospheric pollution conditions of Nanjing by using the observation data of PM$_{2.5}$ concentrations and compositions in Section 3.1. The presence of PM$_{2.5}$ increases the atmospheric heating rate in the suburban below 1.25 km, and the values are more similar to those under clean air conditions. The atmospheric heating rates in the urban centre are 2.8–4.7 K Day$^{-1}$, 2.8–4.6 K Day$^{-1}$, 2.8–5.1 K Day$^{-1}$ and 2.8–4.0 K Day$^{-1}$ in spring, summer, autumn and winter, respectively. The atmospheric heating rates of the suburbs are 2.8–4.4 K Day$^{-1}$, 2.8–4.3 K Day$^{-1}$, 2.8–4.8 K Day$^{-1}$ and 2.8–4.0 K Day$^{-1}$ during the four seasons. Due to the uneven distribution of PM$_{2.5}$ between the urban centre and suburban area, the atmospheric heating rates of the two places are affected differently.
Fig. 6. Atmospheric heating rates in Nanjing during 2014–2015: (a) clean air without PM$_{2.5}$; (b) with PM$_{2.5}$; (c) the impact of PM$_{2.5}$.

The variation of the atmospheric heating rates are the lowest in winter and the highest in summer, which is opposite with the seasonal variations of PM$_{2.5}$ load, indicating that the seasonal variations of solar radiation are still dominantly impact the atmospheric heating rate compared with the influence of PM$_{2.5}$ (Chou, 1986; Liou et al., 1978).

Fig. 6(c) shows the differences of atmospheric heating rates in the urban centre and suburbs of Nanjing caused by PM$_{2.5}$. The presence of PM$_{2.5}$ leads to an increase in the heating rate of the atmospheric.
lower atmosphere below 0.75 km in urban and suburban areas (Busen et al., 1982), and the increase is the largest on the surface. At a height of 1.25 km and above, the heating rates remain constant. In spring, summer, autumn and winter, the increase in lower atmospheric heating rates in urban areas were approximately 0.4–1.1 K Day\(^{-1}\), 0.3–0.9 K Day\(^{-1}\), 0.6–1.6 K Day\(^{-1}\) and 0.5–0.7 K Day\(^{-1}\), while those in suburban areas were approximately 0.3–1.0 K Day\(^{-1}\), 0.25–0.8 K Day\(^{-1}\), 0.5–1.5 K Day\(^{-1}\) and 0.4–0.7 K Day\(^{-1}\). The increase of atmospheric heating rate in the urban centre is always higher than that in the suburbs, which is related to the higher concentration and proportion of absorbing compositions of PM\(_{2.5}\) in urban area. The atmospheric heating rates in the urban centre and suburbs increase more in spring and autumn but less in summer and winter, which is mainly due to the low concentration of PM\(_{2.5}\) in summer and the low solar radiation in winter.

### 3.4 Temperature and Urban Heat Island Profiles

Fig. 7 shows the profiles of atmospheric temperature in Nanjing in different seasons. The atmospheric heating rate is a significant factor which affects the atmospheric temperature profile. The uneven distribution of PM\(_{2.5}\) eventually causes different atmospheric temperature changes in the urban centre and suburbs. Comparing the atmospheric temperature profiles under clean atmosphere conditions (Figs. 7(a), 7(b)) and actual polluted atmospheric conditions (Figs. 7(c), 7(d)), the influence of PM\(_{2.5}\) on atmospheric temperature is mainly concentrated in the lower atmosphere, which is consistent with the vertical distribution of PM\(_{2.5}\). Under the influence of PM\(_{2.5}\), the temperature at the lower atmosphere and surface in the urban centre and suburbs decreased significantly. In spring, summer, autumn and winter, surface temperatures in the urban centre were approximately 283 K, 285 K, 305 K and 277 K, while those in suburban areas were approximately 282 K, 283 K, 304 K and 274 K. It is consistent with previous observations reported in Nanjing (Miao et al., 2012; Yang and Jiang, 2009). The cooling effect of PM\(_{2.5}\) on the temperature is greater in winter than in summer, as the concentration of PM\(_{2.5}\) is larger in winter. Meanwhile, the cooling effect is always greater in the urban centre than the suburbs, which also results from the uneven distribution of PM\(_{2.5}\). As PM\(_{2.5}\) pollution is heavier in the urban centre, it created a greater cooling effect on the temperature near the surface.

Fig. 8 shows the profile of the urban heat island intensity (\(\Delta T\text{UHI}\)) in Nanjing in different seasons. In the absence of PM\(_{2.5}\), the urban heat island intensity of Nanjing city is approximately 2.1–3.1 K, the maximum value of \(\Delta T\text{UHI}\) is in winter and the minimum is in summer. The profiles of \(\Delta T\text{UHI}\) in Fig. 8(a) show the temperature differences between the urban centre and the suburban area under the clean air condition. The values of \(\Delta T\text{UHI}\) are higher in winter and lower in summer at all altitudes, decreasing slightly with elevations below 0.25 km and increasing with heights between 0.25–1.25 km. Lastly, \(\Delta T\text{UHI}\) remains constant until above 1.25 km, where the value was close to the urban heat island intensity at the surface. Fig. 8(b) shows the profiles of \(\Delta T\text{UHI}\) under the polluted air condition in reality, the urban heat island intensity is approximately 2–2.7 K, and PM\(_{2.5}\) makes the \(\Delta T\text{UHI}\) at different altitudes decrease. Meanwhile, the characteristics of \(\Delta T\text{UHI}\) profiles have the same height variation as that in Fig. 8(a). The values of \(\Delta T\text{UHI}\) in winter are still the highest in the four seasons. In spring, the value is close to that in summer. In general, the urban heat island is stronger in winter but weaker in spring and summer.

Fig. 8(c) shows the change of urban heat island intensity profiles (\(\Delta T\text{UHI}\)) impacted by PM\(_{2.5}\) in Nanjing. The negative value of \(\Delta T\text{UHI}\) demonstrates that PM\(_{2.5}\) weakens the urban heat island intensity and the positive value represents the warming effect. As shown in the Fig. 8(c), \(\Delta T\text{UHI}\) is always negative, which means the urban heat island is always weakened by PM\(_{2.5}\). PM\(_{2.5}\) is mainly gathered on the ground. Therefore, PM\(_{2.5}\) can weaken the urban heat island intensity approximately 0.1–0.4 K close to the surface, and the weakening effect is stronger in winter and weaker in summer, which is related to the aerosol concentration and the proportion of black carbon aerosol in winter. At a height of approximately 0.25–1.25 km, the value of \(\Delta T\text{UHI}\) decreases with the increase of the height, and the weakening effect is negligible above 1.75 km. At a height of 0.25–0.75 km, the value of \(\Delta T\text{UHI}\) is smallest in spring and largest in winter, indicating that the influence of PM\(_{2.5}\) on the temperature differences between the urban centre and the suburbs is stronger in spring than in winter. Meanwhile, the weakening effect in the summer is similar to that of the winter, which are both close to −0.2 K. It can be concluded that the small proportion of BC and the lightest
PM$_{2.5}$ load in summer make the weakening effect is not so strong. At the same time, the heavy load of PM$_{2.5}$ in winter has not greatly weakened the $T_{UHI}$ resulting from the smallest solar radiation in the four seasons. As mentioned above, when the proportion of BC is relatively large, it has a heating effect on the atmosphere at a height of 0.25–0.75 km, so the weakening effect on the $T_{UHI}$ is reduced, referring to the larger negative value of $\Delta T_{UHI}$.}

**Fig. 7.** The vertical profiles of atmospheric temperature in Nanjing during 2014–2015: (a) clean air without PM$_{2.5}$ in the urban centre; (b) clean air without PM$_{2.5}$ in the suburbs; (c) polluted air with PM$_{2.5}$ in the urban centre; (d) polluted air with PM$_{2.5}$ in the suburbs.
### 4 CONCLUSIONS

Our study revealed the weakening effect of PM$_{2.5}$ on the UHI intensity by conducting a case experiment in Nanjing. The inhomogeneous distribution of PM$_{2.5}$ concentration and composition in the urban centre and suburban area can cause differences in the radiative forcing effects, atmospheric heating rate, atmospheric temperature and the urban heat island intensity of Nanjing.

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Fig. 8. The urban heat island intensity in Nanjing during 2014–2015: (a) clean air without PM$_{2.5}$; (b) with PM$_{2.5}$; (c) the impact of PM$_{2.5}$.
The analysis of the observation data showed that the concentration of the primary PM$_{2.5}$ components in Nanjing was highest in winter (98–99 µg m$^{-3}$) and lowest in summer (30–32 µg m$^{-3}$). In summer, sulphate and nitrate components were dominant, while in winter, the proportion of black carbon composition increased significantly. It was found that the concentration and the proportion of black carbon composition of PM$_{2.5}$ were higher in the urban centre than the suburbs. Thus, the optical parameters and radiative forcing of PM$_{2.5}$ in the urban centre and suburban area are affected differently. The asymmetry factor in the urban centre was larger in winter (approximately 0.71), but smaller in spring, summer and autumn. The suburban asymmetry factor is larger in summer (approximately 0.72) and smaller in spring and autumn. It can be concluded that the forward scattering ability of the PM$_{2.5}$ in the suburbs was stronger than that in the urban centre. The single scattering albedo (SSA) in the suburbs and the urban centre showed a similar seasonal variation as the maximum value was in summer (0.95–0.97), and the minimum was in winter (0.79–0.82). The optical thickness (AOD) in the urban centre and the suburbs showed similar seasonal variations, the maximum values were in summer and minimum values were in spring. The radiative forcing effects were negative and stronger in the urban centre, that was, the solar radiation reaching the surface in the urban centre was weakened more than that in the suburbs. The positive radiative forcing effects at the top of the boundary layer were also stronger than that in the suburbs. This showed that the cooling effect of PM$_{2.5}$ on the surface in the urban centre is stronger than that in suburban area, as well as the heating effect at the top of boundary layer was also stronger than that in the suburbs due to the inhomogeneous distribution of PM$_{2.5}$ concentration and composition. This causes the change of the temperature difference between the urban centre and the suburbs.

The case study of the urban temperature structure in Nanjing showed that the atmospheric heating rate in the urban centre and the suburbs was low in winter and high in summer. The presence of PM$_{2.5}$ led to an increase in the heating rate below 0.75 km in the urban centre and suburbs. The increase was the largest at the surface, and it was almost zero at 1.25 km and above. Due to the uneven distribution of PM$_{2.5}$, the atmospheric heating rates of the urban centre and the suburbs were affected by different amplitudes. In spring, summer, autumn and winter, the increases of lower atmospheric heating rate in the urban centre were approximately 0.4–1.1 K day$^{-1}$, 0.3–0.9 K day$^{-1}$, 0.6–1.6 K day$^{-1}$, and 0.5–0.7 K day$^{-1}$, respectively, while those in the suburbs were approximately 0.3–1.0 K day$^{-1}$, 0.25–0.8 K day$^{-1}$, 0.5–1.5 K day$^{-1}$, and 0.4–0.7 K day$^{-1}$, respectively. Due to the low concentration of PM$_{2.5}$ in summer and the low solar radiation in winter, the atmospheric heating rates in the urban centre and the suburbs increased greatly in spring and autumn but were lower in summer and winter. PM$_{2.5}$ had a significant cooling effect on the surface and lower atmospheric temperature both in the urban and suburban areas. In the reality, the surface air temperatures in the urban centre in spring, summer, autumn and winter were approximately 283 K, 285 K, 305 K, and 277 K, while those in suburbs were approximately 282 K, 283 K, 304 K, and 274 K. The seasonal variations of PM$_{2.5}$ concentration showed that the PM$_{2.5}$ was higher in winter and lower in summer and the concentration was always higher in the urban centre than the suburbs. Therefore, the cooling effect is greater in winter than in summer as well as stronger in the urban centre than the suburbs. Meanwhile, the urban heat island intensity in Nanjing showed a similar seasonal variation as the PM$_{2.5}$ concentration, it was higher in winter and lower in spring and summer. Essentially, PM$_{2.5}$ could weaken the urban heat island intensity by 0.1–0.4 K. The smaller PM$_{2.5}$ concentration and proportion of black carbon composition in summer worked together to weaken the UHI intensity less when compared to winter. Taking the highest solar radiation reaching the surface in summer into consideration, the concentration and the composition of PM$_{2.5}$ played a significant role in the change of the urban heat island intensity. When the proportion of black carbon composition was relatively large, it had a heating effect on the atmosphere at a height of 0.25–0.75 km. Therefore, the influence of PM$_{2.5}$ on the temperature difference between the urban centre and the suburbs at 0.25–0.75 km was lower in winter and higher in spring.

In general, the urban climate is a complex system impacted not only by PM$_{2.5}$ but also numerous factors including surface albedo, roughness lengths, relative humidity, emissivity and other mechanisms (Garuma, 2018; Khare et al., 2020). It is impossible to extract the PM$_{2.5}$ as a single atmospheric parameter and investigate its impact on the urban temperature structure separate to...
the other contributors. Due to these factors, we conducted the case study using a one-dimensional box model to examine this. However, unanswered questions remain. In our future work, we will further investigate the set of urban parameters to make the box model more complete. Despite that, the night time UHI intensity would also be accounted for in creating a new version of the box model. The diurnal variation of atmospheric temperature structure will aid us in understanding the feedback of PM$_{2.5}$ on the urban climate. The results can be replicated in other cities which can help the urban planning and make the urban climate better.

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DISCLAIMER

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES


Kuhlmann, J., Quaas, J. (2010). How can aerosols affect the Asian summer monsoon? Assessment during three consecutive pre-monsoon seasons from CALIPSO satellite data. Atmos. Chem. Phys. 10, 7017–7039. https://doi.org/10.5194/acp-10-4673-2010


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