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Interaction Between Planetary Boundary Layer and $PM_{2.5}$ Pollution in Megacities in China: a Review

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Abstract

Purpose of Review During the past decades, the number and size of megacities have been growing dramatically in China. Most of Chinese megacities are suffering from heavy $PM_{2.5}$ pollution. In the pollution formation, the planetary boundary layer (PBL) plays an important role. This review is aimed at presenting the current state of understanding of the PBL-$PM_{2.5}$ interaction in megacities, as well as to identify the main gaps in current knowledge and further research needs.

Recent Findings The PBL is critical to the formation of urban $PM_{2.5}$ pollution at multiple temporal scales, ranging from diurnal change to seasonal variation. For the essential PBL structure/process in pollution, the coastal megacities have different concerns from the mountainous or land-locked megacities. In the coastal cities, the recirculation induced by sea-land breeze can accumulate pollutants, whereas in the valley/basin, the blocking effects of terrains can lead to stagnant conditions and thermal inversion. Within a megacity, although the urbanization-induced land use change can cause thermodynamic perturbations and facilitate the development of PBL, the increases in emissions outweigh this impact, resulting in a net increase of aerosol concentration. Moreover, the aerosol radiative effects can modify the PBL by heating the upper layers and reducing the surface heat flux, suppressing the PBL and exacerbating the pollution.

Summary This review presented the PBL-$PM_{2.5}$ interaction in 13 Chinese megacities with various geographic conditions and elucidated the critical influencing processes. To further understand the complicated interactions, long-term observations of meteorology and aerosol properties with multi-layers in the PBL need to be implemented.

Keywords Megacity · Planetary boundary layer · Urbanization · Local circulation · Aerosol radiative effect

Introduction

Megacities are usually defined as urban agglomerations with a population exceeding 10 million [1, 2•]. During the second half of the twentieth century, the number and size of megacities increased dramatically, especially in the developing world [2•], which enforce substantial and extended effects on environmental conditions [3••, 4–6]. The air pollution has become one of the most important problems of megacities [1, 3••].

Based on the population data of municipalities and prefectural level cities in 2017, there are in total 13 megacities in China (Table 1), all of which are suffering from high loadings of $PM_{2.5}$ (particles with an aerodynamic diameter of less than 2.5 μm), with an annual value significantly exceeding the WHO guideline of 10 μg m^{-3}. $PM_{2.5}$ not only has detrimental impacts on visibility and human health [7, 8] but also influences the ecosystem, local/regional weather, and climate change [9, 10, 11•]. The frequent occurrence of $PM_{2.5}$ pollution episodes in China is primarily caused by the high emissions of anthropogenic pollutants [3••, 12], except for the occasional occurrence of dust events in spring [13]. Industry, traffic exhaust, power plants, domestic heating, fertilizer

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application, and farming all contribute to the high emissions of pollutants [4, 14, 15]. Organic matter and SNA (sum of sulfur, nitrate, and ammonium) are found to be the dominant $PM_{2.5}$ components in the megacities in China [3••], on average which contribute approximately 26% and 40%, respectively.

In addition to the emissions, the pollution level for a megacity is largely determined by the structure and process of planetary boundary layer (PBL) [16–19], which is the lowest portion of the troposphere. The PBL represents sensitive and variable coupling agents that regulate the fluxes of energy, momentum, and matter between the surface and the free troposphere [20]. After being emitted into the atmosphere, the fate of pollutants (e.g., dispersion, mixing, transport, transformation, deposition) is strongly dependent on the PBL charactersitics [18, 21]. In the vertical direction, the thermal stratification controls the intensity of thermal buoyancy, and the PBL wind in combination with the surface roughness establishes the strength of mechanical turbulence [16, 18]. Together they regulate the upward dispersion of pollutants and the exchanging of cleaner air from above [18]. The concept of boundary layer height (BLH) is widely used to characterize the vertical limit of the dilution volume of pollutants [22, 23, 24•, 25]. In the horizontal dimension, the wind fields below the BLH are critical to the pollutant dilution and the distance of downwind transport [18, 26]. When suspended in the PBL, the pollutants may induce feedback to PBL structure and undergo physical/chemical transformations, which are relevant to meteorological factors such as humidity, temperature, solar radiation, and the presence of certain atmospheric substances [11•, 18, 27–30].

Urbanization is one of the most essential human-induced changes in land use [31], resulting in a high percentage of asphalt and concrete in the megacities. Due to the differences in surface properties and wasted heat from anthropogenic activities, the air temperature in the densely built-up urban areas can be warmer than that of rural surroundings by up to several degrees Celsius [31, 32], especially during the night. This heating phenomenon is called the urban heat island (UHI), which not only impacts the thermal stability of PBL directly [33, 34] but also affects the transport of pollutants by inducing local thermal circulation [18]. In a megacity, the distribution of the buildings and urban structures also dynamically influence air flow and microclimate, enhance turbulence, and modify the mixing, dispersion, and deposition of pollutants within street canyons [5, 31, 35, 36].

The megacities in China are with a variety of geographic conditions (e.g., inland, coastal, mountainous) (Table 1). The urban PBL structure and wind fields inside and their subsequent interaction and effect on transport and dispersion of pollutants are highly dependent on the existence of terrains/seas [37, 38]. Besides, the large-scale synoptic pattern also plays a vital role in modulating the PBL structure through warm/cold advections [16, 39, 40]. Hence, the complex interactions between PBL and aerosol pollution in megacities include the links shown in Fig. 1 and have the following specifics: (1) nonlinear interactions between surface properties, emissions, and meteorology; (2) multiple spatial and temporal scales; and (3) complicated feedbacks between PBL and aerosols.

Recently, the importance of PBL dynamics and physics in controlling key aspects of $PM_{2.5}$ pollution in China is becoming increasingly recognized [11•, 24•, 41, 42]. This paper intends to review the current status of studies (mostly after 2015) on the complex PBL-pollution interactions in

Table 1 Population and $PM_{2.5}$ concentration of megacities in China in 2017

Megacity	Population (million)	$PM_{2.5}$ annual average concentration (μg m^{-3})	Location
Beijing	21.71	58	North China Plain
Tianjin	10.50	62	
Shijiazhuang	10.88	86	
Baoding	11.68	84	
Linyi	10.56	60	
Shanghai	24.18	39	Yangtze River Delta
Suzhou	10.68	42	
Guangzhou	14.50	35	Pearl River Delta
Shenzhen	12.53	28	
Chongqing	33.90	45	Sichuan Basin
Chengdu	16.04	56	
Wuhan	10.89	52	Central China
Nanyang	10.05	56	

Data sources: National Bureau of Statistics and Ministry of Ecology and Environment of the People's Republic of China. Note that Baoding, Linyi and Nanyang have a relatively smaller portion of the urban population at prefectural level compared with other cities, but all have dense populations and the potential to achive a higher urbanization level in the near future megacities in different geographic regions with various climates and to identify the main gaps in our current knowledge as well as further research needs in this important field of research. The remainder of this review is organized according to the geographic locations of megacities. The most polluted North China Plain (NCP) is first presented in the next section, then followed by Yangtze River Delta (YRD), Pearl River Delta (PRD), Sichuan Basin (SCB), and Central China.

North China Plain

There are 5 megacities (Beijing, Tianjin, Shijiazhuang, Baoding, and Linyi) in the NCP (32–40° N, 114–121° E) (Table 1), which is one of the most polluted and densely populated regions in China. Located in a warm temperate zone, the NCP has a semi-humid climate with four distinctive seasons: short springs and autumns and long summers and winters. The mean annual precipitation in the NCP is 500–600 mm, and nearly 60% of annual precipitation occurs in summer [43]. On a seasonal basis, the $PM_{2.5}$ pollution in the NCP is most massive in winter, followed by autumn and spring, and reaches its minimum in summer [24•, 44]. This seasonal variation in pollution is not only attributed to the changes in emissions (e.g., heating in winter) and precipitation but also to the differences in the BLH [21, 24•, 45•].

Surrounded by mountains and seas, the geography conditions impact the PBL and air quality in the megacities of the NCP in complex ways [45•, 46, 47]. The plain is bordered on the north by the Yan Mountains, on the west by the Taihang Mountains and the Henan highlands, and on the southwest by the Tongbai and Dabie Mountains. From northeast to southeast, it faces the Bohai Sea, the hills of Shandong Peninsula, and the Yellow Sea. The terrains behave like a dustpan that accumulates air pollutants in the cities close to the mountains, such as Beijing, Shijiazhuang, and Baoding [1]. Under weak synoptic situations, the blocking effects of mountains can suppress the downward transport of momentum from free troposphere to the PBL over these megacities, leading to calm wind and weak mixing condition and exacerbating the $PM_{2.5}$ pollution [47].

In addition, the local thermal contrast between the mountains (land) and plains (sea) can induce thermal wind systems (e.g., mountain-plain breeze and sea-land breeze) under synoptically quiescent conditions [18, 37, 45•]. The UHI can also result in a local breeze between the downtown areas and surrounding rural areas [48, 49], but it is usually weaker than the mountain-plain breeze and sea-land breeze in the NCP [50]. The thermodynamic perturbations and turbulent mixings induced by urbanization on surface properties can facilitate the growth of urban PBL and the dispersion of $PM_{2.5}$ [51], while the urbanization-induced increases in aerosol emissions outweigh those of land use modification, resulting in a net increase of aerosol concentration in megacities [52, 53•]. The local thermally circulations in the NCP are generally suboptimal pollution ventilators: first, the speed of these winds is usually rather low (less than 7 ms^{-1}) [18]; second, they are closed circulation systems that accumulate pollutants in a limited box [45•]; and third, they exhibit a diurnal reversal in the direction of winds (e.g., upslope/inland breeze during the day and downslope/offshore breeze after sunset) that leads to a recirculation of pollutants [45•, 54].

On a regional scale, the megacities in the NCP usually experience heavy $PM_{2.5}$ pollution simultaneously, which is caused by specific synoptic patterns with warm advection [24•]. To address the relationships between synoptic pattern and aerosol pollution, several studies applied T-mode principle component analysis [55] to classify the pressure fields in NCP objectively and investigated the PBL structure [24•, 39, 56, 57]. The heavy pollution episodes in Beijing are often associated with a high-pressure system located to the east or southeast of the city at 925-hPa level, accompanying with southerly PBL winds that bring in pollutants from southern regions [24•, 39, 57]. In the vertical direction, the warm advection above the PBL induced by synoptic forcings can strengthen the inversion and thereby inhibit the growth of PBL [16, 24•, 39, 57, 58], suppressing the diluting effect of vertical mixing and leading to a high $PM_{2.5}$ concentration near surface. The mountain-plain breeze circulation can also enhance the existing inversion [45•, 54, 58]. In the afternoon, the return flow of the closed circulation of mountain-plain breeze can superimpose on the prevailing wind and bring warmer air from the mountains to the neighboring cities (e.g., Beijing, Shijiazhuang, and Baoding), strengthening the inversion layer and leading to a shallow PBL [45•, 54, 58].

During the heavy pollution episodes, the cumulative explosive growths of $PM_{2.5}$ mass were often found to be associated with stable atmospheric stratification, southerly slight or calm winds, and near-surface anomalous inversion [59]. The high concentrations of aerosols can enhance the stability of urban PBL and in turn decrease the BLH and consequently further exacerbate the pollution [54, 60, 61•, 62–64], which has been known as the “two-way feedback mechanism” [11•]. The decreased PBL can increase relative humidity (RH) by weakening the diffusion of water vapor, facilitating the formation of secondary inorganic aerosols and worsening the air quality. This RH-related mechanism is self-amplifying, leading to faster formation and accumulation of aerosols within the PBL [65]. Among the compositions of particulate matter, the black carbon (BC) aerosol, intensively emitted by residential combustion, industrial activities, and transportation, has been identified as the main culprit causing the PBL-aerosol feedback in the megacities [27, 61•]. By heating the upper PBL and reducing the surface heat flux, the aerosol radiative effect of light-absorbing BC aerosol can substantially suppress the development of PBL [66]. This process has been referred to as the "dome effect" of BC, which played a vital role in the formation of prolonging haze events in the NCP during December 2013 [61•]. In addition, the light-scattering aerosols also play an important role in lowering BLH by cooling the land surface, which leads to an increase in RH and accumulations of aerosols [67, 68].

The contributions of the PBL meteorology and aerosol feedback to $PM_{2.5}$ concentration in Beijing have been quantitatively examined, which were responsible for approximately 84% of the explosive growth of $PM_{2.5}$ during the cumulative stage [69]. Since the heating/diming efficiency is sensitive to the vertical distribution of aerosols, it is necessary to update the vertical profile of aerosols in the model to improve the simulation of PBL-aerosol feedback in the megacities [70]. Moreover, the vertical distributions of temperature, humidity, and precursor gases also play a role in modulating the chemical reaction rate and gas-particle partitioning at different heights [11•, 29, 30, 68]. For instance, due to the more cooling condition aloft that favors the gas-particle partitioning, the mass fraction and concentration of particulate nitrate were reported higher aloft (e.g., 260 m) than at the ground level in Beijing [29]. The nighttime integrated production of particulate nitrate in the residual layer above can significantly increase the near-surface aerosol concentration in the next morning through vertical mixing [71].

Yangtze River Delta

The YRD (28–33° N, 118–123° E), located in the coastal regions of eastern China, has two megacities (Shanghai and Suzhou) (Table 1) and enjoys a humid subtropical monsoon climate with four distinct seasons. The mean annual precipitation in YRD is 1000–1400 mm, and the rainy season lasts from April to September. Similar to the NCP, the $PM_{2.5}$ concentration in YRD also peaks in winter and has the lowest value in summer, which is influenced by the seasonal variations in emission, BLH, prevailing wind, and precipitation [21, 24•, 72, 73]. Comparing with the $PM_{2.5}$ pollution in NCP, the pollution in YRD is lighter (Table 1), but the annual average pollution concentration is still significantly higher than the guideline of WHO.

During the past decades, the YRD has been experiencing an intensive urban expansion and become the largest metropolitan cluster in the world [53•]. This remarkable urbanization can lead to a decrease in surface and lower tropospheric $PM_{2.5}$ concentration by increasing the BLH and ventilation over the urban areas, favoring the dispersion of pollutants from urbanized areas to their immediate vicinities [53•, 74]; however, the increased pollutant emissions add even more, resulting in a net increase in the occurrence of haze, particularly in winer [53•].

In the YRD, the vertical distribution of $PM_{2.5}$ in the urban areas is observed to be strongly correlated with the meteorological variables within PBL, such as temperature, RH, and the existence of inversion [75, 76]. Based on the long-term continuous measurements in the western YRD, the complex linkages between the PBL meteorology and the diurnal evolution of pollutants have been recognized [60, 77], including the fumigation of residual-layer plumes, the turbulent mixing of pollutants within a convective PBL, and the formation of elevated pollution layer.

Given the importance of BC for air quality and regional climate [61•], in December 2013, an intensive field campaign was launched in Shanghai to unravel the vertical structures of PBL and BC [76]. During a diurnal cycle, the BC

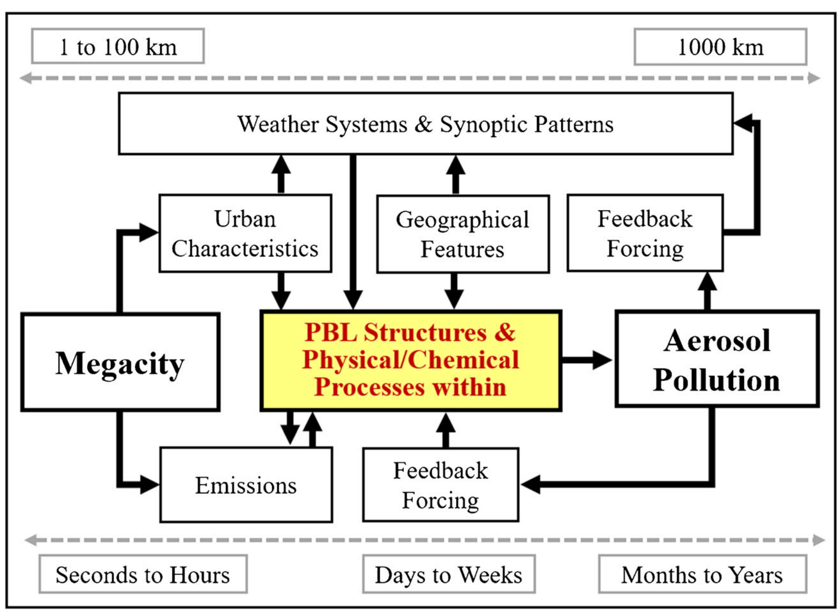

Fig. 1 Schematic showing the complex interactions between PBL and aerosol pollution in a megacity

concentration at ground level was modulated by both the emission and BLH, leading to the highest BC level in the morning associated with high traffic emission and shallow BLH. In the afternoon and after sunset, distinct vertical profiles of BC were observed using the tether balloon [76]. The profiles at night showed strong gradients from the high concentration at ground level to low concentration near the top of PBL at around 200 m AGL, while in the afternoon, the BC particles were well mixed in the PBL with a depth of more than 1000 m. The BC particles can modify the PBL meteorology and air quality. For example, in the harvest seasons, the biomass burning plumes with considerable amounts of light-absorbing aerosols (e.g., BC and brown carbon), are found to cause a significant cooling at the ground surface and warming in the atmosphere, resulting in the "dome effect" over the YRD. Such a modification can suppress the vertical mixing and dispersion of pollutants and lead to heavy pollution in the lower PBL [60], which is not only limited to biomass burning events. In winter, the shallow PBL in YRD often coincides with high extinction of aerosols at low altitude, leading to an enhanced cooling effect within the near-surface layer and the suppression of BLH [72]. The PBL-pollution interaction is a common phenomenon across the YRD, which can further modify cloud properties and precipitation patterns [60].

From the perspective of synoptic condition, under the control of slowly migrating anti-cyclone, the subsidence airflow can suppress the vertical mixing and favor the accumulation of pollutants within a relatively shallow PBL over the YRD [73, 78–80], notably when the subsidence thermal inversion or nocturnal surface inversion formed [80]. The equal pressure field associated with strong thermal inversion and high RH is another typical pattern that causes heavy pollution in the YRD [81]. Besides, the strong northwesterly frontal airflow can cause trans-border transport of aerosols from the NCP to the YRD, leading to a deteriorated air quality in the YRD megacities [79]. Under stagnant synoptic conditions when the east-to-southeast winds prevail in the YRD, the sea-land breeze would frequently develop, resulting in the recirculation of airflow in the coastal cities [82, 83], which allows the accumulation of aerosols and leads to heavy pollution events.

Pearl River Delta

The PRD (21–25° N, 111–115° E), located in the coastal region of southern China, has two megacities (Table 1): Guangzhou and Shenzhen. It is controlled by a subtropical monsoon climate characterized by warm winters and hot and humid summers. The annual precipitation is 1600–1900 mm, with rainy season lasting from April to September [84]. The $PM_{2.5}$ pollution in PRD is heaviest during winter, followed by spring and autumn, and summer is the cleanest season [21, 85]. Although the air quality in the megacities of PRD is much better than those northern megacities in China, it still cannot meet the annual guideline of the WHO (Table 1).

Based on the continuous multi-wavelength Raman and polarization lidar observations in the PRD, lofted layers of aerosol were often observed above the PBL [84]. The heights of these lofted layers exhibit a seasonal dependence, with heights below 2 km AGL during winter and heights up to 5 km AGL in spring. The occurrence of lofted aerosol layers may be related to the regional transport of pollutants, diurnal growth/evolution of PBL, and local thermally driven circulations [84, 86]. The lofted aerosols can impact the precipitation and lightning in the PRD: it may suppress the light and moderate rainfall, but enhance the heavy rainfall and lightning [87].

In the PRD, tropical cyclone is a typical weather condition responsible for poor air quality [88•], especially during summer and autumn. The peripheral subsidence airflow induced by the tropical cyclones can reduce the BLH in the megacities and produce stagnation of surface flow, thereby limiting the vertical mixing and horizontal diffusion of locally emitted pollutants [88•]. The subsidence is often associated with thermal inversion layers over the urban areas, which can strongly inhibit the growth of PBL. During the intensive PBL observations over the PRD in October 2004 and July 2006, the occurrence frequency of inversion associated with the subsidence of tropical cyclones was ~ 52%, and most of the inversion layers occurred at the height below 1000 m AGL [88•]. Another typical situation that can lead to inversion and heavy pollution is the warm period before a cold front, in which the occurrence frequency of inversion was ~ 77% during the intensive PBL observations, and the surface inversion occurred more frequently than the elevated inversion [88•]. In addition, two kinds of typical PBL structure that leads to poor air quality in PRD were observed during the winter in 2013 [86]: weak vertical diffusion ability type and weak horizontal transportation ability type. The first type is featured by moderate wind speed, consistent wind direction, and thick inversion at 600–1000 m AGL, and the latter is characterized by calm wind, varying wind direction, and shallow intense surface inversion layer [86].

Similar to the YRD, when the PRD is under the control of weak synoptic systems (e.g., anticyclone), the sea-land breeze frequently develops, which can lead to the formation of inversion layers and the recirculation of pollutants [86, 88•, 89]. For example, the pollutants are observed initially transported away from Xinken (22.36° N, 113.35° E), but subsequently returned [88•]. Besides, the high urbanization level in the PRD can enhance turbulent mixing within the PBL and modify local thermal circulations, such as the initiation of UHI circulation and strengthening of sea breeze [90]. Despite the urbanization processes which increase the BLH over the urban areas in the PRD, the induced surface UHI convergence and intensified sea breeze may still act to exacerbate the pollution through enhancing the pollutant recirculation [89, 90].

Sichuan Basin

The SCB (28–32° N, 103–108° E) is the most developed region in southwestern China, located east to the Tibetan Plateau, with the Qin Mountains to the north and the Yunnan-Guizhou Plateau to the south. There are two megacities in the SCB: Chongqing and Chengdu (Table 1). The SCB is generally at low altitudes of ~ 500 m. It has subtropical monsoon climate with high temperature and RH. The annual precipitation is 1000–1300 mm, with rainy season lasting from June to October. This region has long been recognized as a low visibility area with high aerosol pollution level [91]. During an annual cycle, the most serious $PM_{2.5}$ pollution occurs in winter, and the lowest pollution level is in summer [21, 24•, 92].

Due to the blocking effects of surrounding terrains, the wind in the SCB is quite weak, especially in the western part [93]. From the clean stage to polluted stage, the wind speed in Chengdu typically shows a substantial decrease [94]. The lower wind speed is unfavorable to the diffusion of pollutants. The wind direction also differs under various polluted/clean stages. For example, the stronger northeasterly wind often prevails during the clean period in Chengdu, which carries cleaner air masses from the less polluted areas to the city [94]; while during the polluted period, the wind usually comes from the south of Chengdu, where many industrial cities are located (e.g., Luzhou, Panzhihua), leading to the transport of pollutants and the deterioration of air quality in Chengdu [94]. Moreover, the mountain ranges to the west of Chengdu act as a barrier to the air flow from the east and cause the accumulation of pollutants in front of the mountain [93, 95]. In addition to the weak wind, the high RH is also critical to the pollution in the SCB. The aqueous-phase reaction is a key formation pathway for the $PM_{2.5}$ species [94].

Since the weak 10-m wind along with shallow PBL tends to restrict the diffusion of $PM_{2.5}$, a specific day can be defined as an air stagnation day when it has no precipitation and the combining index of 10-m wind speed and BLH are below a threshold [47]. It is found that the SCB is exposed to the air stagnation conditions for approximately half of the year. From 2013 to 2016, the occurrence frequency of air stagnation days in SCB during winter was ~ 77% in SCB [93]. The BLHs in the margins of the basin are lower than those at the center during winter, and the areas with the shallowest PBL are exactly where Chengdu and Chongqing are located [93], leading to an extremely high occurrence frequency of air stagnation and heavy pollution in these two megacities.

Similar to those megacities in the NCP, Chengdu and Chongqing also often experience the stagnation conditions and resultant heavy $PM_{2.5}$ pollution simultaneously [24•]. Comparing with the clean days, those days with heavy pollution in the SCB are typically characterized by low BLH and strong thermal inversion at 900-hPa level [24•]. The strong thermal inversion is often associated with the low-pressure system at 700-hPa level, induced by the dynamic and thermodynamic effects of the Tibetan Plateau [96]. Comparing with other flat regions, the air quality issue associated with thermal inversion is further aggravated in the SCB since the source area is topographically confined, and the inversion lid usually lies at a lower elevation than the basin sides. Moreover, the surrounding elevated terrains could induce lee eddies in the basin, which could trap the pollutants, leading to heavy pollution in the whole SCB [24•].

Besides, during the harvest season from February to October, biomass burning is an essential contributor to airborne particles in the SCB, owing to the widespread burning activity after harvest and large consumption of agricultural residues for energy source [97]. For instance, the emitted particles from crop residues were observed to rapidly increase the $PM_{2.5}$ concentration in Chengdu [97]. During a diurnal cycle, the pollution is often characterized by dramatic build-up of aerosol concentration at night, when intensive burning of crop residues is carried out and the BLH is decreased to the minimum level [97]. Since the biomass burning plumes contain light-absorbing aerosols, they could cause significant impact to the PBL dynamics through the “dome effect” [11•, 60, 98].

Central China

There are three provinces in Central China (29–36° N, 108–117° E), including Henan, Hubei, and Hunan. The subtropical monsoon climate controls the southern part of Central China, while the northern part is influenced by the temperate monsoon climate, leading to distinct annual precipitation from the south (~ 1500 mm) to the north (~ 500 mm). It has two megacities: Wuhan and Nanyang (Table 1). Comparing with those abovementioned regions, where the PBL-pollution linkages have been extensively investigated, the studies on the $PM_{2.5}$ pollution and PBL structure in Central China are quite limited. Only a few studies focused on the air quality issues in Wuhan.

Similar to the seasonal change of pollution in the NCP, the $PM_{2.5}$ concentration in Wuhan also demonstrates a pronounced seasonal variation, with the peak in winter and minimum in summer, which is modulated by the changes in precipitation, emission, and PBL structure [21, 24•, 99]. Based on radiosonde data and $PM_{2.5}$ measurements in summer from 2013 to 2016, the relationships between the BLH and $PM_{2.5}$ pollution in Wuhan were elucidated [100]. Noticeable diurnal variation of BLH is revealed by the sounding data, which peaks in the afternoon and decreases quickly after sunset. Such a diurnal change in BLH is reversely correlated with the diurnal variation of $PM_{2.5}$ concentration. The day-to-day co-variations in BLH and $PM_{2.5}$ concentrations were also examined, and significant anti-correlation was found. These results imply the critical roles of PBL in the $PM_{2.5}$ pollution in Wuhan [100]. Two synoptic patterns characterized by northeasterly winds are found to be associated with heavy pollution in Wuhan. Influencing by the northeasterly prevailing winds, the pollutants emitted from the NCP and the YRD can be transported to Wuhan, worsening the pollution [100]. The case study of $PM_{2.5}$ pollution on 12 October 2014 also emphasizes the significant impact of long-range transport of pollutants from NCP to Wuhan [101], which could contribute ~ 60% of $PM_{2.5}$ in Wuhan. Besides, the intensive biomass burnings in and around Wuhan are found to be critical to the air quality during the summer and autumn [102, 103]. During the pollution episodes dominated by biomass burning, the aerosol plume can induce "doom effect" to modify the PBL thermal structure and exacerbate the pollution in Central China [11•, 98].

Conclusions

In 2017, there are in total 13 megacities in China, including five cities in the NCP (Beijing, Tianjin, Shijiazhuang, Baoding, and Linyi), two cities in the YRD (Shanghai and Suzhou), two cities in the PRD (Guangzhou and Shenzhen), two cities in the SCB (Chongqing and Chengdu), and two cities in Central China (Wuhan and Nanyang). Most of these megacities are suffering from heavy $PM_{2.5}$ pollution. Table 2 summarizes the recent studies on the PBL and aerosol pollution in China. The air quality issues and key influencing processes in these megacities differ significantly, which are relevant to several factors, such as meteorology, topography, demography, transportation, fuel quality, energy usage, and the level of industrialization, urbanization, and socio-economic development.

As the buffer zone between the surface and the free troposphere, PBL meteorology is one of the most critical factors regulating the $PM_{2.5}$ pollution in the urban areas. The BLH directly determines the vertical volume for the dispersion and

Table 2 Summary of recent studies (mostly after 2015) on the PBL and aerosol pollution in Chinese megacities

Location	Research focus	References
North China Plain	Synoptic pattern	Miao et al. [39, 57], Ye et al. [56]
	Mountain-plain and sea-land breezes	Miao et al. [28, 33, 45•, 54], Hu et al. [58]
	Impacts of urbanization	Yu et al. [34], Zheng et al. [49], Miao et al. [35, 36, 50], Chen et al. [51]
	Aerosol radiative feedback	Miao et al. [54], Zhong et al. [59, 68, 69], Ding et al. [61•], Quan et al. [62], Gao et al. [63], Huang et al. [66], Qiu et al. [67], Wang et al. [70]
Yangtze River Delta	Synoptic pattern	Yang et al. [40], Shu et al. [73], Leng et al. [78], Kang et al. [79], Liao et al. [80], Zhou et al. [82]
	Sea-land breeze	Huang et al. [83]
	Impacts of urbanization	Zhong et al. [53•], Xie et al. [74]
	Aerosol radiative feedback	Ding et al. [60], Sun et al. [72], Li et al. [76], Zhong et al. [11•]
Pearl River Delta	Synoptic pattern	Wu et al. [88•]
	Sea-land breeze	Li et al. [86], Lo et al. [89]
	Impacts of urbanization	Li et al. [90], Lo et al. [89]
	Aerosol radiative feedback	Zhong et al. [11•]
Sichuan Basin	Synoptic pattern	Miao et al. [24•], Ning et al. [96]
	Topographic impacts	Miao et al. [24•], Wang et al. [47] Liao et al. [93, 95]
	Aerosol radiative feedback	Zhong et al. [11•]
Central China	Synoptic pattern	Miao et al. [24•], Liu et al. [100]
	Cross-border pollutant transportation	Liu et al. [100], Lu et al. [101]
	Aerosol radiative feedback	Zhong et al. [11•]

dilution of pollutants; thus, its change modulates the $PM_{2.5}$ pollution at multiple temporal scales, including the seasonal, daily, and hourly variations. On a seasonal basis, all the megacities in China experience the most serious $PM_{2.5}$ pollution in winter, relevant primarily to the lowest seasonally averaged BLH in that season. The day-to-day variations of pollution in megacities are closely governed by the evolution of synoptic condition and the forced PBL structure. The synoptic forcings often lead to concurrent drops of BLH, and synchronous increases of $PM_{2.5}$ concentration in several megacities belong to a region, such as the NCP, SCB, and Central China. During a diurnal cycle, the daily curve of $PM_{2.5}$ concentration often shows two maxima, one in the early morning and one in the evening, consistent with the low values of BLH and the peaks in activities which generate pollution at that time.

For the PBL structures and processes, the coastal megacities may have different concerns to the mountainous or land-locked megacities. In the YRD and PRD, the frequently developed sea-land breeze can induce recirculation to accumulate the pollutants in the coastal cities. In the NCP, the terrains behave like a dustpan that accumulates pollutants in the cities close to the mountains, such as Beijing, Shijiazhuang, and Baoding. The diurnal reversal in the upslope and downslope winds also leads a recirculation of pollutants in these cities. During the daytime, the closed thermal circulation developed between the mountains and plains can bring the aloft warmer air to the cities, further strengthening the inversion and inhibiting the vertical mixing of pollutants. In the SCB, the cities are topographically confined, with frequent occurence of weak near-surface wind and strong thermal inversion above PBL. As a result, the cities in SCBare exposed to the air stagnation conditions for approximately half of the year, leading to the frequent heavy pollution there. In Central China, the air quality in megacities is usually influenced by the long-range transport of pollutants from upstream regions, such as the NCP and YRD.

In the past decades, most cities in China have been experiencing intensive urban expansion and substantial land use change. The induced thermodynamic perturbations and turbulent mixings can facilitate the growth of PBL and the dispersion of pollutants; however, the urbanization-induced increases in emissions outweigh those of land use modification, resulting in a net increase of aerosol in megacities. Last but not least, during heavy pollution episodes, the aerosol radiative effects can significantly modify the PBL structure in megacities, which can heat the upper PBL and reduce the surface heat flux, leading to the suppression of the PBL development and the deterioration of air quality.

Although great efforts have been devoted to elucidating the complex interactions between the PBL and aerosol pollution in China in recent years, most studies focused on Beijing, Shanghai, Guangzhou, and Chengdu, and the PBL structure/process in the other megacities is still far from well known, especially for Central China. In addition to those 13 megacities listed in Table 1, the urban PBLs in other heavily polluted and densely populated cities in China also need further investigations, such as Zhengzhou [24•], Lanzhou [104], Xi'an [105], Harbin [24•], and Shenyang [106].

Besides, at present, most regions of China still lack adequate long-term continuous PBL observation. The vertical distributions of both meteorological variables and aerosol properties within the PBL in megacities need to be better understood and resolved in the model, as they dominate the local energetics and mass budgets for more accurate forecasts. This requires observation campaigns over key megacities to utilize advanced instruments to obtain high-resolution vertical profiles.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflicts of interest.

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