15-Year PM$_{2.5}$ Trends in the Pearl River Delta Region and Hong Kong from Satellite Observation

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ABSTRACT

Rapid economic development and urbanization have caused severe pollution from PM$_{2.5}$ in the Pearl River Delta (PRD) region of China. Characterizing the long-term PM$_{2.5}$ trends is a basic requirement for evaluating the effectiveness of the implemented control measures and for guiding future policies. Traditional characterization has relied on fixed-site measurements, leading to incomplete spatial and temporal coverage. In this study, we took advantage of satellite-derived PM$_{2.5}$ data at a resolution of 0.01° × 0.01° and assessed the long-term PM$_{2.5}$ trends on a city scale in the PRD region and on a district scale in Hong Kong from 2001 to 2015. The results of our analysis showed that the PM$_{2.5}$ concentration in the PRD region and Hong Kong worsened during the 10th Five-Year-Plan (FYP) period (2001–2005) and started to improve during the 11th FYP period (2006–2010). The improvement accelerated during the 12th FYP period (2011–2015). These trends were in line with the trends of air-pollutant emissions. In addition, the cities in the central area of the PRD region experienced higher PM$_{2.5}$ concentration increase during the 10th FYP period and a greater reduction in the concentration afterward during the 11th FYP period than those in the non-central area of the PRD region. During the 12th FYP period, PM$_{2.5}$ concentrations substantially lessened for most of the cities in the PRD region, particularly for those in the non-central area of the PRD region. For Hong Kong, the rates of increase and decrease in the PM$_{2.5}$ concentration generally exhibited gradients from the northwest to the southeast, suggesting effects from the regional transport of air pollutants. A group of districts in the central urban area of Hong Kong also experienced a substantial decline in the PM$_{2.5}$ concentration during the 11th and 12th FYP periods, suggesting the beneficial effects of local control efforts.

Keywords: PM$_{2.5}$; Satellite remote sensing; Long-term trend; Megacity; Air pollution.

INTRODUCTION

The Pearl River Delta (PRD) was the first region to develop in China when the country started the implementation of its reform and opening-up policies in the 1980s. With an area of about 56,000 km$^2$ and about 59 million people, the PRD region has been identified as one of the largest urban areas in the world (World Bank, 2015). The rapid economic development and urbanization, however, produced intense emission of air pollutants and caused severe pollution from PM$_{2.5}$ (fine particulate matter with aerodynamic diameters smaller than 2.5 µm), thus receiving increasing attention from the public and the government (Zheng et al., 2010; Zhong et al., 2013; Lu et al., 2016).

To improve air quality in the PRD region, great efforts have been made by the Guangdong Province and Hong Kong governments to formulate and issue various control measures and policies to reduce emission of air pollutants during the past few Five-Year-Plan (FYP) periods (Zhong et al., 2013). On September 10, 2013, the State Council issued the Air Pollution Prevention and Control Action Plan as the guideline for air-pollution control measures in the future, which aimed to reduce PM$_{2.5}$ concentration by up to 15% in the PRD region from 2012 to 2017. In response to the various implemented control strategies in the PRD region, PM$_{2.5}$ concentration was likely to have undergone great spatiotemporal variation during the past few FYP periods. Characterization of the long-term PM$_{2.5}$ concentration...
trends is therefore a basic requirement for evaluating the effectiveness of the implemented control measures and for guiding future policies (Li et al., 2015b).

Traditional characterization of the long-term PM$_{2.5}$ concentration trends has relied on fixed-site measurements (Lang et al., 2017). The first Regional Air Quality Monitoring Network (RAQMN) in China, which included 16 stations, was established and has operated in the PRD region since November 2005 (Zhong et al., 2013). The enhanced monitoring of PM$_{2.5}$ concentration in China has only been available since 2013 (Lin et al., 2015). A review of ground-based measurements from the PRD RAQMN from 2006 to 2011 showed that the annual PM$_{2.5}$ concentration declined by 14.1% from 2006 to 2011, with a peak in 2007 (Zhong et al., 2013). Wang et al. (2014) collected the published PM$_{2.5}$ concentration data in the PRD region from various sources (including published papers, statistical yearbooks, and the internet) from 2000 to 2010, which showed that the annual average of PM$_{2.5}$ concentration had a peak in 2004 and declined afterwards. All of these studies were based on limited fixed-site observations or reported campaign data, leading to incomplete spatial and temporal coverage. Even with the enhanced fixed-site monitoring of PM$_{2.5}$ concentration since 2013, it is still difficult for such monitoring to fully capture the spatial variability in PM$_{2.5}$ concentration on a large spatial scale (Lu et al., 2017).

Compared with fixed-site measurements, recent development in satellite-based remote sensing provides a useful alternative for estimating PM$_{2.5}$ concentration on a large spatial scale (van Donkelaar et al., 2010; Brauer et al., 2012; Li et al., 2015a; Bilal et al., 2016; Karimian et al., 2016; Lin et al., 2016b; Zhang et al., 2017). With the use of the satellite-retrieved PM$_{2.5}$ concentrations at a resolution of 10 km, Ma et al. (2015) showed that PM$_{2.5}$ concentration remained relatively constant from 2004 to 2007, following by a decreasing trend from 2008 to 2013 in the PRD region. Estimate of PM$_{2.5}$ concentrations at a high spatial resolution of 1 km is also of critical importance for air-pollution assessment, particularly in dense urban areas (Hu et al., 2014; Lao et al., 2017; Wong et al., 2017; Zhang et al., 2018a, b).

To better describe air pollution for dense urban areas, Lin et al. (2016) built a long-term PM$_{2.5}$ data set with a spatial resolution of 0.01° × 0.01° in the PRD region and analyzed the characteristics of the spatial distribution of PM$_{2.5}$ concentration. The high-resolution PM$_{2.5}$ data set provides good opportunities for characterizing PM$_{2.5}$ trends on urban and district scales. In this study, we took advantage of the high-resolution satellite-derived PM$_{2.5}$ data set in the PRD region and aimed to comprehensively assess the long-term PM$_{2.5}$ trends in the PRD region from 2001 to 2015. PM$_{2.5}$ trends were characterized on a city scale in the PRD region and on a district scale in Hong Kong during the 10th (2001–2005), 11th (2006–2010), and 12th (2011–2015) FYP periods.

**DATA**

**Study Region**

The PRD region, as shown in Fig. S1, is located on the southern coast of China. The left panel plots the topography of the PRD region and marks the locations of the cities. The PRD region is a large plain surrounded by mountains on three sides (west, north, and east) and by ocean to the south. The basin-shaped topography confines dispersion of air pollutants when the background wind is weak. The PRD region comprises nine major cities in Guangdong Province and two special administrative regions (Hong Kong [HK] and Macau [MC]). Hong Kong has one of the highest population densities among megacities in the world. About 7.5 million inhabitants are living on a group of islands with a total area of 1000 km$^2$. Hong Kong has a hilly topography and comprises 18 districts, as shown in the right panel.

**Emission Trends in the PRD**

To reduce the PM$_{2.5}$ concentration, the Guangdong Province and Hong Kong governments have promulgated a series of control measures to reduce emissions of primary particles and precursors of secondary particles (e.g., sulfur dioxide [SO$_2$], nitrogen oxides [NO$_x$], and volatile organic compounds [VOCs]) during the past few FYP periods. We obtained the emission data from 2001 to 2015 for Guangdong Province (total suspended particles [TSP], SO$_2$, and NO$_x$) and Hong Kong (fine suspended particles [FSP], SO$_2$, NO$_x$, and VOCs) from the China statistical yearbook (http://www.stats.gov.cn/tjsj/ndsj/) and the Hong Kong Environmental Protection Department (http://www.epd.gov.hk/epd/english/environmentinhk/air/data/emission_inv e.html), respectively. Fig. 1(a) plots the 15-year variations of the normalized emissions of TSP, SO$_2$, and NO$_x$ in Guangdong Province. The yearly emissions were normalized by the data in the beginning year. Emission of SO$_2$ steadily increased by 33% during the 10th FYP period, mainly due to rapid economic growth, significant fossil-fuel consumption, and a lag in the introduction of desulfurization equipment (Lu et al., 2013; Zhao et al., 2013). In response to the implementation of sulfur-control measures for power plants and industrial sectors, SO$_2$ emission declined by 47% during the 11th and 12th FYP periods. Emission of TSP generally increased during the 10th FYP period and reached a maximum in 2003. It started to decline during the 11th FYP period but remained steady during the 12th FYP period. The China statistical yearbook started reporting the emission of NO$_x$ in 2011. The results showed that emission of NO$_x$ declined by 28% during the 12th FYP period, mainly because of the deployment of NO$_x$ removal equipment in power plants and industrial sectors (Xia et al., 2016).

Fig. 1(b) plots the 15-year variations of the normalized emissions of FSP, SO$_2$, NO$_x$, and VOCs in Hong Kong. Emission of SO$_2$ generally increased during the 10th FYP period and reached a maximum in 2004. It then declined by 78% during the 11th and 12th FYP periods. Emission of FSP generally remained steady during the 10th FYP period and reached a maximum in 2004. It then declined by 39% during the 11th and the 12th FYP periods. Emission of NO$_x$ remained steady during the 10th FYP period and then declined by 26% during the 11th and 12th FYP periods. Emission of VOCs steadily declined by 49% during this 15-year period. Generally, emissions of most air pollutants increased or
Satellite-derived PM$_{2.5}$

To facilitate air-quality studies in dense urban areas, a PM$_{2.5}$ data set at a high spatial resolution of $0.01^\circ \times 0.01^\circ$ was built for the PRD region in our previous study (http://envf.ust.hk/dataview/aod2pm/current) (Lin et al., 2016a). The high-resolution satellite data provide good opportunities for characterizing the PM$_{2.5}$ trends on city and district scales. Fig. S2 shows the inter-annual variations of the satellite-derived and ground-observed PM$_{2.5}$ concentrations in the PRD region from 2001 to 2015. The satellite-derived and ground-observed measurements have similar spatial patterns, with much higher PM$_{2.5}$ concentrations near the center of the PRD region. In addition, the satellite observation shows that PM$_{2.5}$ concentrations remained high from 2004 to 2007 and then declined. This trend is consistent with those of the air-pollutant emissions and PM$_{2.5}$ concentrations from other studies (Zhong et al., 2013; Wang et al., 2014; Ma et al., 2015).

We further take Hong Kong as an example to characterize the PM$_{2.5}$ distribution within a city. Fig. S3 shows the inter-annual variations of the satellite-derived and ground-observed PM$_{2.5}$ concentrations in Hong Kong from 2001 to 2015. Both measurements show much higher PM$_{2.5}$ concentrations in the central urban areas (with dense tall buildings and heavy traffic emissions) and in the northwest of Hong Kong (adjacent to the central area of the PRD region and the most susceptible to the long-range transport of pollutants). In addition, observations from both satellite and ground show that PM$_{2.5}$ concentration reached a maximum in 2004 and then gradually declined.

Fig. S4 shows the evaluation of the annual mean of the satellite-derived PM$_{2.5}$ concentration against ground observation in the PRD region from 2001 to 2015. The correlation coefficient was estimated to be 0.86 ($N = 363$), which is comparable to those of 0.76–0.82 ($N = 974–1145$) in the U.S. and 0.74–0.79 ($N = 45–68$) in China from other studies (van Donkelaar et al., 2010, 2013; Geng et al., 2015; van Donkelaar et al., 2015; Peng et al., 2016). The root mean square error (RMSE), mean absolute error, and mean absolute percentage error are within 5 µg m$^{-3}$, 5 µg m$^{-3}$, and 10%, respectively, suggesting the good accuracy of the data set. We also evaluate the monthly mean of the satellite-derived PM$_{2.5}$ concentration using all available ground observations in the PRD region from 2001 to 2015, as shown in Fig. S5. The correlation coefficient, RMSE, and mean absolute percentage error are about 0.80 ($N = 4610$), within 15 µg m$^{-3}$, and within 25%, respectively.

Because the traditional MODIS AOD product has a resolution of 10 km, we also derive the PM$_{2.5}$ data at a resolution of 10 km by averaging the 1-km PM$_{2.5}$ data and then assess the potential difference in the distribution of PM$_{2.5}$ concentrations at the two resolutions. Fig. S6 plots the spatial distributions of the 15-year means of PM$_{2.5}$ concentrations in the PRD region at resolutions of 1 km and 10 km. The use of PM$_{2.5}$ data at a higher spatial resolution can provide more information on the spatial variability in PM$_{2.5}$ concentration, which can be important for the air quality studies on urban scales.

RESULTS

15-Year Variation of PM$_{2.5}$ Concentration in the PRD

On the basis of the high-resolution satellite data, the inter-annual variations of the spatial mean PM$_{2.5}$ concentrations in the PRD region and different cities are illustrated in Fig. 2. For the entire PRD region, the PM$_{2.5}$ concentrations remained high during 2004 to 2007 and then generally declined. The maximal annual mean of the PM$_{2.5}$ concentration for the PRD region was around 50 µg m$^{-3}$ (mean and standard deviation of 48.4 ± 10.7 µg m$^{-3}$ in 2004 and 49.9 ± 10.1 µg m$^{-3}$ in 2007). It is encouraging to find that the annual mean PM$_{2.5}$ concentration for the PRD region decreased to 30.9 ± 5.0 µg m$^{-3}$ in 2015, a level lower than the World Health Organization Interim Target 1 (WHO IT-1) and the current national ambient air-quality standard (NAAQS), 35 µg m$^{-3}$.

In addition, PM$_{2.5}$ levels substantially differed among...
the cities. PM$_{2.5}$ concentrations in the cities in the central area of the PRD region (e.g., FS, ZS, and GZ) were much higher than those in the non-central area of the PRD region (e.g., JM, HZ, and HK). In the most polluted city (i.e., FS), the maximal annual mean of the PM$_{2.5}$ concentration reached around 70 µg m$^{-3}$ (68.0 ± 7.4 µg m$^{-3}$ in 2004 and 67.7 ± 6.7 µg m$^{-3}$ in 2007). In the least polluted city (i.e., HK), the maximal annual mean PM$_{2.5}$ concentration was 38.3 ± 4.4 µg m$^{-3}$ in 2004. After the substantial declines in PM$_{2.5}$ concentrations since 2007, the annual mean PM$_{2.5}$ concentrations dropped to a level lower than the WHO IT-1 for most cities except for FS (39.5 ± 3.5 µg m$^{-3}$) and DG (36.1 ± 4.1 µg m$^{-3}$) in 2015. The lowest PM$_{2.5}$ concentration in 2015 was observed in HK, which had a level of 24.5 ± 2.5 µg m$^{-3}$. It is also noted that these city-average PM$_{2.5}$ concentrations in 2015 were still higher than the WHO IT-2 (25 µg m$^{-3}$) for most cities and much higher than the WHO IT-3 (15 µg m$^{-3}$) and air-quality guideline (AQG, 10 µg m$^{-3}$) for all of the cities, suggesting that more control efforts are required to further improve air quality in the region.

Fig. 3(a) shows the inter-annual variations in the percentage of area where PM$_{2.5}$ concentrations exceeded the WHO IT-1 (i.e., current NAAQS) in the entire PRD region and in different cities from 2001 to 2015. For the entire PRD region, the percentage of areas with PM$_{2.5}$ concentrations exceeding the WHO IT-1 was higher than 90% during the most polluted period (2004–2008). The percentage of areas with PM$_{2.5}$ concentrations exceeding the WHO IT-1 then substantially declined and reached 20.1% for the PRD region in 2015. These areas with PM$_{2.5}$ concentrations exceeding the WHO IT-1 were mostly in the center of the PRD region, as shown in Fig. S2.

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For the polluted cities (e.g., FS, ZS, DG, GZ, ZH, and ZQ), almost the entire area had PM$_{2.5}$ concentrations exceeding the WHO IT-1 during almost the entire period except for during the past few years. Even for the least polluted city in the PRD region (i.e., HK), about 81.0% of the area had PM$_{2.5}$ concentrations exceeding the WHO IT-1 in 2004. After the great improvement in air quality, the percentage of areas with PM$_{2.5}$ concentrations exceeding the WHO IT-1 substantially declined for all cities. The percentage of areas with PM$_{2.5}$ concentrations exceeding the WHO IT-1 ranged from 0% (in ZH, MC, and HK) to 86.7% (in FS) in 2015.

Fig. 3(b) shows the inter-annual variations in the percentage of area where PM$_{2.5}$ concentrations exceeded the WHO IT-2 in the entire PRD region and in different cities from 2001 to 2015. For the entire PRD region, almost 100% of the area had PM$_{2.5}$ concentrations exceeding the WHO IT-2 throughout the entire period except for in 2015 (89.8%). The percentage of areas with PM$_{2.5}$ concentrations exceeding the WHO IT-2 ranged from 36.8% in Hong Kong to about 100% in polluted cities such as FS, ZS, DG, GZ, and ZQ in 2015. If we further judge air quality by the stricter standards, the entire PRD region (i.e., 100% of the area) still suffered from pollution, with PM$_{2.5}$ concentrations exceeding the WHO IT-3 and AQG in 2015.

**PM$_{2.5}$ Trends for Cities in the PRD**

We separated the assessment of PM$_{2.5}$ concentration trends by the three FYP periods. Fig. 4(a) shows the spatial distributions of PM$_{2.5}$ concentration trends in the PRD region during the three FYP periods. The PM$_{2.5}$ concentration in the PRD region increased during the 10th FYP period and started to improve during the 11th FYP period. Improvement accelerated during the 12th FYP period. The spatial means of PM$_{2.5}$ concentration trends for the entire PRD region were estimated to be 1.31 µg m$^{-3}$ yr$^{-1}$, –1.54 µg m$^{-3}$ yr$^{-1}$, and –2.36 µg m$^{-3}$ yr$^{-1}$ during the 10th, 11th, and 12th FYP periods, respectively. Substantial regional differences in the PM$_{2.5}$ concentration trends were also observed across the PRD region. The central area of the PRD region had more PM$_{2.5}$ deterioration during the 10th FYP period and greater improvement during the 11th FYP period than the non-central region. During the 12th FYP period, PM$_{2.5}$ concentrations extensively declined in the PRD region, particularly in the non-central regions.
Fig. 3. Inter-annual variations in the percentage of area where PM$_{2.5}$ concentration exceeded the WHO (a) IT-1 and (b) IT-2 in the entire PRD region (black line) and in different cities (colored lines) from 2001 to 2015.

Fig. 4. (a) Spatial distribution of PM$_{2.5}$ trends in the PRD region during the three FYP periods. (b) Mean PM$_{2.5}$ trends for different cities in the PRD region during the three FYP periods.

Fig. 4(b) shows the spatial means of PM$_{2.5}$ concentration trends for different cities during the three FYP periods (see detailed values in Table S1). During the 10th FYP period, cities in the center of the PRD region had more deterioration in the PM$_{2.5}$ concentration. The increasing rates for PM$_{2.5}$ concentration were estimated to be 2.75 µg m$^{-3}$ yr$^{-1}$ and 2.07 µg m$^{-3}$ yr$^{-1}$ for FS and GZ, respectively. During the 11th FYP period, cities in the center of the PRD region also had more substantial declines in PM$_{2.5}$ concentration than those in the non-central area of the PRD region. The most substantial decline in PM$_{2.5}$ concentration was observed in FS, which occurred at a rate of –2.23 µg m$^{-3}$ yr$^{-1}$. During the 12th FYP period, PM$_{2.5}$ concentrations substantially declined in most cities of the PRD region. The highest improvement rates of PM$_{2.5}$ concentration were observed in ZS and ZH, which occurred at rates of –3.68 µg m$^{-3}$ yr$^{-1}$ and –3.38 µg m$^{-3}$ yr$^{-1}$, respectively.

PM$_{2.5}$ Trends for Districts in HK

On the basis of the high-resolution satellite data, PM$_{2.5}$ concentration trends for different districts in Hong Kong were also assessed. Fig. 5(a) shows the spatial distributions
Fig. 5. (a) Spatial distributions of PM$_{2.5}$ concentration trends in Hong Kong during the three FYP periods. (b) Mean PM$_{2.5}$ concentration trends for different districts in Hong Kong during the three FYP periods.

of PM$_{2.5}$ concentration trends in Hong Kong during the three FYP periods. The PM$_{2.5}$ concentration generally increased during the 10th FYP period and declined during the 11th and 12th FYP periods. The spatial means of PM$_{2.5}$ concentration trends for Hong Kong were estimated to be 0.92 µg m$^{-3}$ yr$^{-1}$, -0.81 µg m$^{-3}$ yr$^{-1}$, and -1.64 µg m$^{-3}$ yr$^{-1}$ during the 10th, 11th, and 12th FYP periods, respectively. Substantial regional differences in PM$_{2.5}$ concentration trends were also observed across the city. The increasing rate of PM$_{2.5}$ concentration during the 10th FYP period and the decreasing rate of PM$_{2.5}$ concentration during the 11th and 12th FYP periods generally had gradients from northwest to southeast.

Fig. 5(b) shows the spatial means of PM$_{2.5}$ trends for different districts during the three FYP periods (see detailed values in Table S2). During the 10th FYP period, districts in northwest Hong Kong had the largest worsening of PM$_{2.5}$ concentration (e.g., 1.36 µg m$^{-3}$ yr$^{-1}$ for TM, 1.31 µg m$^{-3}$ yr$^{-1}$ for YL, and 1.34 µg m$^{-3}$ yr$^{-1}$ for NO). PM$_{2.5}$ concentrations started to decline during the 11th FYP period. The most and least substantial improvement in PM$_{2.5}$ concentration were observed in NO and SO at rates of -1.02 µg m$^{-3}$ yr$^{-1}$ and -0.34 µg m$^{-3}$ yr$^{-1}$, respectively. During the 12th FYP period, the most substantial improvements in PM$_{2.5}$ concentration were observed in districts in northwest Hong Kong (e.g., -2.65 µg m$^{-3}$ yr$^{-1}$ for TM and -2.05 µg m$^{-3}$ yr$^{-1}$ for YL). It is also noted that a group of districts in the center urban area of Hong Kong (e.g., KI and TW) also had substantial improvements in PM$_{2.5}$ concentration during the 11th and 12th FYP periods.

DISCUSSION

The long-term variation in PM$_{2.5}$ concentration is a result of multiple factors such as the emission control measures applied to different sources, relocation of manufacturing facilities, the nonlinear nature of chemical reactions, and the meteorological effect (Li et al., 2015b). Li et al. (2014) differentiated the effects of wind and non-wind (e.g., emissions) changes and showed that the long-term variation in PM concentration in Hong Kong was dominated by the non-wind effect (e.g., emissions). In this study, the increase in PM$_{2.5}$ concentration during the 10th FYP period and the decline in PM$_{2.5}$ concentration during the 11th and 12th FYP periods were in line with the trends of emissions of air pollutants (Lu et al., 2013; Zhao et al., 2013). Control policies therefore may have already helped to improve local and regional air-pollution problems to some extent. On the other hand, the PM$_{2.5}$ concentration in the PRD region still largely exceeds the stricter air-quality standards, such as the WHO IT-2, IT-3, and AQG, suggesting that more control efforts are required to further reduce the pollutant concentrations in the future, especially for the cities in the center of the PRD region.

For Hong Kong, the increasing rate for PM$_{2.5}$ concentration during the 10th FYP period and decreasing rate for PM$_{2.5}$ concentration during the 11th and the 12th FYP period generally had a gradient from northwest to southeast. It suggest that PM$_{2.5}$ pollution in Hong Kong may be largely affected by long-range transport from the center of the PRD region. In addition, a group of districts
in the central urban area of Hong Kong (e.g., KI, TW, and SS) also had substantial improvement in PM$_{2.5}$ concentration during the 11$^{th}$ and the 12$^{th}$ FYP periods, suggesting the beneficial effects of local air-quality control efforts.

**CONCLUSION**

In this study, we took advantage of satellite-derived PM$_{2.5}$ data at a resolution of 0.01° × 0.01° and comprehensively assessed the long-term PM$_{2.5}$ concentration trends in the PRD region and Hong Kong from 2001 to 2015. The results of our analysis showed that PM$_{2.5}$ concentrations in the PRD region and Hong Kong increased during the 10$^{th}$ FYP period and started to decrease during the 11$^{th}$ FYP period. This improvement accelerated during the 12$^{th}$ FYP period—results that were in line with the trends of emissions of air pollutants. In addition, the PM$_{2.5}$ concentration trends substantially differed among cities in the PRD region and among the districts in Hong Kong. The cities in the central area of the PRD region experienced higher PM$_{2.5}$ concentration increase during the 10$^{th}$ FYP period and a greater reduction in the concentration during the 11$^{th}$ FYP period than those in the non-central area of the PRD region. During the 12$^{th}$ FYP period, PM$_{2.5}$ concentrations substantially lessened for most of the cities in the PRD region, particularly for those in the non-central area of the PRD region. For Hong Kong, the rates of increase and decrease in the PM$_{2.5}$ concentration generally displayed gradients from the northwest to the southeast, suggesting effects from the regional transport of air pollutants. In addition, a group of districts in the central urban area of Hong Kong also experienced a substantial decline in the PM$_{2.5}$ concentration during the 11$^{th}$ and 12$^{th}$ FYP periods, suggesting the effects of local control efforts.

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**SUPPLEMENTARY MATERIAL**

Supplementary data associated with this article can be found in the online version at http://www.aair.org.

**REFERENCE**


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