



Review

Aerosol pollution in China: Present and future impact on environment

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ABSTRACT

With its dense population, rapid economic growth and dramatic rate of urbanization, China is experiencing extreme air pollution problems. This is particularly the case in Central-Eastern China (CEC), where the two major cities of Beijing and Tianjin are located, in the Yangtze-River Delta (YRD) with the city of Shanghai, and in the Pearl-River Delta (PRD) with the mega-city of Guangzhou. Space observations show that the atmospheric aerosol load in these three regions is considerably higher than, for example, in the urbanized regions of Europe and North America. The high aerosol concentrations in these regions have raised many environmental problems, such as impact on human health, visibility, and climate changes. In this paper, several crucial issues regarding aerosol pollution in these highly populated regions (CEC, YRD, and PRD) are discussed, including (1) when the aerosol load starts to rapidly increase in these regions; (2) how the high aerosol concentrations affects the environment; and (3) what the potential consequences are under possible low aerosol load in these regions. Discussion on these crucial issues might lead to some insight for better understanding of the characterizations of aerosol pollution due to the rapid economical development in China.

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1. Introduction

Rapidly increasing urbanization will be a major environmental driving force in the 21st century, affecting air quality on all scales – local, regional, and global. According to recent United Nations estimates, the number of mega cities (with more than 10 million inhabitants) has increased from 1 in 1950 to 19 in 2000, and is

expected to reach 23 by 2015. In eastern coast China, there is a concentration of many large cities; including four mega cities (see Fig. 1). Such dense urbanization has important effects on atmospheric environment. Satellite observations have revealed much higher aerosol pollution in eastern China than in eastern US (Tie et al., 2006). Such high aerosol pollution has primarily resulted from human activities. According to statistics of the International Energy Agency, the energy consumption in China has increased more than 300% from 1973 to 2002. The use of coal during 2003 amounted to 1502 TG (10^{12} g) in China and 976 TG in the US. By contrast, the use of crude oil was 234 TG in China and 864 TG in the US. The use

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Fig. 1. The distribution of large cities in China. The small red dots represent cities with population of more than 1 million, and the bigger orange dots show the locations of mega cities with population of more than 10 million. The blue circles indicate the CEC, YRD, and PRD regions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

of coal is known to produce more SO_2 and aerosol particles than oil fuel. As a result, extensive coal burning results in very heavy aerosol pollution in eastern coast China (Cao et al., 2003a, b; Deng et al., 2008; Sun et al., 2004; Wu, Tie, & Deng, 2006; Wu et al., 2005; Zhang et al., 2006).

High aerosol pollution causes wide-ranging consequences for human health, cultivated and natural ecosystems, visibility, weather, radiative forcing, and tropospheric oxidation (self-cleaning) capacity (Tie et al., 2005). For climatic effects, aerosol leads to direct radiative forcing because it scatters (Charlson, Lovelock, Andreae, & Warren, 1987; Charlson et al., 1992; Tegen, Koch, Laci, & Sato, 2000) and absorbs (Jacobson, 2001; Ramanathan, Crutzen, & Kiehl, 2001; Ramanathan & Vogelmann, 1997) solar radiation in the atmosphere. Aerosol also alters the formation and precipitation efficiency of liquid water, ice, and mixed-phase clouds (Charlson et al., 1987), thereby causing indirect radiative forcing associated with these changes in cloud properties. In addition to climate and weather, aerosol has important impacts on human health. The Chinese Academy on Environmental Planning blamed air pollution for 411,000 premature deaths in China in 2003, primarily from lung and heart diseases. Tie, Wu, and Brasseur (2009) analyzed a 52-year history of surface measurements of haze data in the PRD region, to show that the dramatic increase in the occurrence of aerosol pollution events between 1954 and 2006 was followed by significant enhancement of the incidence of lung cancer. High aerosol concentration often produces low visibility. According to Deng et al. (2008), the occurrence of low visibility days increased dramatically after 1975 due to high aerosol concentration in the PRD region.

In this paper, we will focus on the discussion of characterization of aerosol pollution in eastern coast China, including the three fast developing areas (CEC, YRD, and PRD). Several crucial issues regarding the impact of aerosol pollution on environment in these

regions will also be discussed in order to better understand the pollution control strategy and to improve the aerosol pollution in this region.

2. Present aerosol pollution in China

2.1. Characterizations of aerosol pollution

There are two major kinds of aerosol pollution in China: (1) anthropogenic aerosol pollution and (2) mineral dust aerosol pollution. According to Guinot et al. (2006), the anthropogenic aerosol particles in Beijing region were dominated by organic matter (52%) and sulfate particles (28%), followed by nitrate (9%), ammonium (8%) and soot (3%) particles. These particles are generally small (radius less than $0.5 \mu\text{m}$). As will be discussed in the following sections, these small particles play a dominant role in causing low visibility and affecting human health. Because these small particles are mainly produced by anthropogenic emissions (traffic, industrial, biomass burning, etc.), their high concentrations are generally correlated to the major cities (see Fig. 2(a)), such as the CEC, YRD, and PRD regions shown in Fig. 1. The sizes of mineral dust particles are relatively large (radius greater than $0.5 \mu\text{m}$) compared to anthropogenic particles (Zhang, Han, Cheng, & Tao, 2009). There are several distinguishing characters between the small anthropogenic particles and the large mineral dust particles. (a) There are very strong seasonal variations for mineral dust particles compared to anthropogenic particles. According to Zhang et al. (2006), mineral dust events occur mainly in spring, while anthropogenic aerosol pollution exists in all seasons. (b) The spatial distributions are very different between mineral dust and anthropogenic aerosols. As shown in Fig. 2(b), the highest dust concentrations are located in the Gobi Desert and the dust gets transported to northern China with western prevailing winds during spring. As a result, the dust pollutions have important envi-

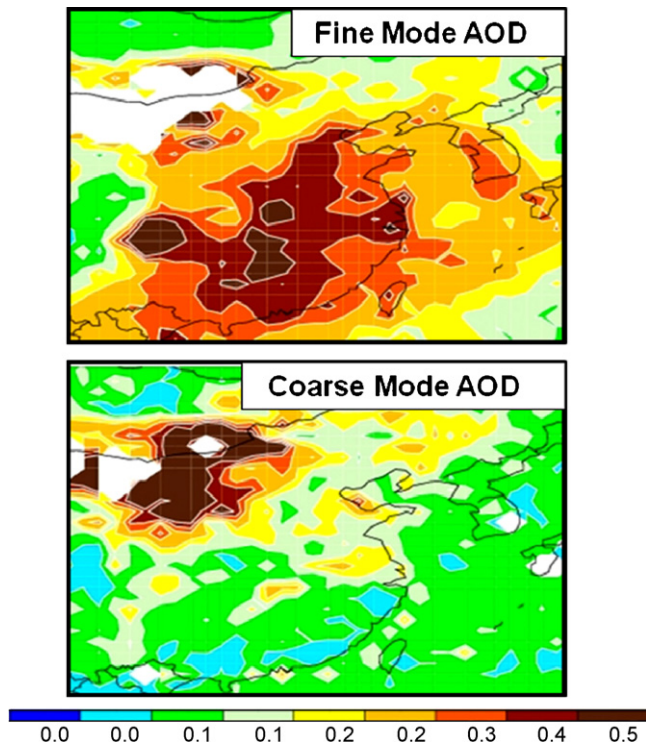


Fig. 2. Satellite measurement (MODIS) of aerosol optical depth (AOD) in China. The upper and lower panels show the AOD in fine (radius $< 0.5 \mu\text{m}$) and coarse modes, respectively, in September 2000 (Tie et al., 2006).

ronmental impacts in the CEC region, but only minor influences in the YRD and PRD regions. (c) The chemical composition of mineral dust is quite different from anthropogenic aerosols, consisting of positive (alkaline) ions Mg^{2+} , Ca^{2+} , K^+ , etc. However, anthropogenic particles consist mostly of negative ions (acidic species) SO_4^{2-} , NO_3^- and insoluble chemical components (carbon black and organic carbon) (Guinot et al., 2006; Sun et al., 2004). During raining time, the co-occurrence of dust and anthropogenic aerosol particles results in neutralizing acidity in precipitation, leading to less acid rain in the CEC region. (d) The causes of dust events are mainly due to natural forcing, such as wind speed, soil, and convective conditions. By contrast, anthropogenic aerosol pollutions are mostly produced by human activities, such as urbanization and industrialization. In the following sections, we will focus on anthropogenic aerosol pollutions, which are the major environmental problems we are facing due to the rapid economical development in China.

2.2. Long-term trend of aerosol pollution

In order to understand the causes and to establish effective control strategies for anthropogenic aerosol pollution, we first need to know when high anthropogenic aerosol pollutions start to rapidly increase. A long-term (1954–2005) series of aerosol optical extinction coefficients (AEC in the unit of Mm^{-1} ; $1 \text{Mm}^{-1} = 10^{-6} \text{m}^{-1}$) in the PRD region (shown in Fig. 3) is used to examine the historical trend of aerosols in eastern coast China (Deng et al., 2008; Tie et al., 2009). Fig. 3 indicates that before 1970s, anthropogenic aerosol pollutions were very low. The aerosol levels started increasing in the mid 1970s, when economical development rapidly increased. Aerosol pollution reached a maximum in the mid 1980s, and has remained high up to the present. In order to analyze this long-term trend, three periods are distinguished by using the derivative of the

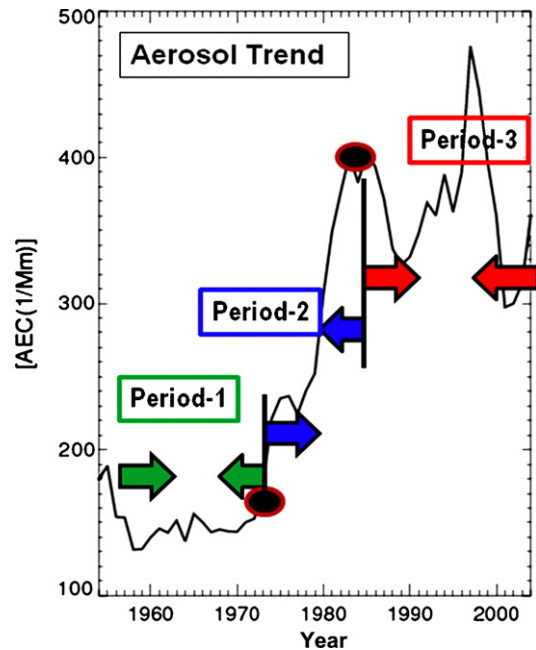


Fig. 3. The long-term trend of aerosol extinction coefficient (AEC) recorded in Guangzhou, China from 1950s to 2000s (Tie et al., 2009).

aerosol trend corresponding to economical development and the use of clean energy:

$$D_{At} = \frac{dA_t}{dt} \sim E_i - E_c,$$

where A_t represents the aerosol load; D_{At} , the derivative of aerosol load (trend); E_i , the increase of aerosol emission due to economical development; and E_c , the decrease of aerosol emission due to the use of clean energy. During Period-1 (before 1970s), both the E_i and E_c were small, and the trend of aerosols was close to zero. During Period-2 (from mid 1970s to mid 1980s), the aerosol trend increased rapidly at this initial stage of economical development in China during which the use of clean energy was limited ($E_i \gg E_c$). During Period-3 (from mid 1980s to the present), the aerosol trend (D_{At}) decreased to a small value (close to zero) indicating that though economical development remained fast, the use of clean energy increased significantly (E_i is close to E_c), keeping the aerosol load at a high, but constant level. At present, aerosol level is decreasing in developed countries (such as the US and European countries), indicating that their E_c is larger than E_i . With more effort in using clean energy in China, the aerosol level will eventually decrease, which can be considered as Period-4 (a future period). It should be mentioned that there will be some negative consequences with the reduction of aerosol pollutions, such as increase in O_3 concentrations as has already occurred in the US and European countries.

2.3. Effects of aerosol pollution

2.3.1. Effect on visibility

Aerosols have significant impact on visibility, and poor visibility can stop highway transportation, causing difficulties in daily life and economical development. Fig. 4 shows an example of highway closure due to low visibility between Tianjin and Beijing (two mega cities in the CEC region), as often happened in spring in the CEC region. The assessment of aerosol particles affecting visibility requires detailed aerosol information, such as their size and composition. Important factors which need to be considered include



Fig. 4. Highway is closed due to extremely low visibility between Tianjin and Beijing, the two mega cities in the CEC region.

hygroscopic growth of aerosol particles and interactions between aerosols and fog formation.

First, aerosol particles scatter and absorb solar radiation to reduce visible light. Under high aerosol concentrations, the reduction of visible light produces low visibility. According to Deng et al. (2008) in the PRD region, when aerosol mass concentrations (PM₁₀, total aerosol mass with radius less than 10 μm) exceed 100 μg/m³, low visibility (less than 10 km) occurs. At the present, PM₁₀ is widely used as an aerosol pollution index by environmental protection agencies. However, the value of PM₁₀ is not a single indicator to determine visibility range. For example, for two different conditions with equal mass concentrations (M₁ = M₂) but different mean aerosol radius (R₁ ≠ R₂), the visibility range (VR) can be significantly different as illustrated by the following expressions (Xie, Tao, & Zhou, 1999):

$$VR = \frac{3.912}{\beta} \sim \frac{1}{A}, \quad (1)$$

$$\frac{VR_1}{VR_2} = \frac{A_2}{A_1} = \left(\frac{R_2^2}{R_1^2}\right) \left(\frac{N_2}{N_1}\right) = \frac{R_1}{R_2}, \quad (2)$$

where VR₁ and VR₂ represent the visibility range under the two conditions, respectively; β the aerosol extinction coefficient; A₁ and A₂ the aerosol areas (πR₁²N₁ and πR₂²N₂); and N₁ and N₂ the aerosol particle numbers. Because aerosol particle numbers can be calculated by N = M/(4ρπR³/3) with the condition of M₁ = M₂, the ratio of N₂/N₁ can be expressed by N₂/N₁ = (R₁³/R₂³).

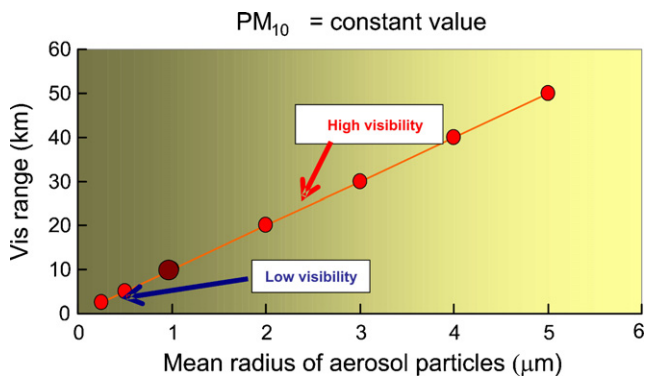


Fig. 5. Visibility range (km) as a function of aerosol particle size (μm) for the same aerosol mass concentration (e.g. PM₁₀ = 100 μg/m³). For example, when the aerosol particles are smaller than 1 μm, the visibility is less than 10 km (poor visibility). With increasing aerosol particle size (greater than 1 μm), visibility is significantly improved while not changing aerosol mass concentration.

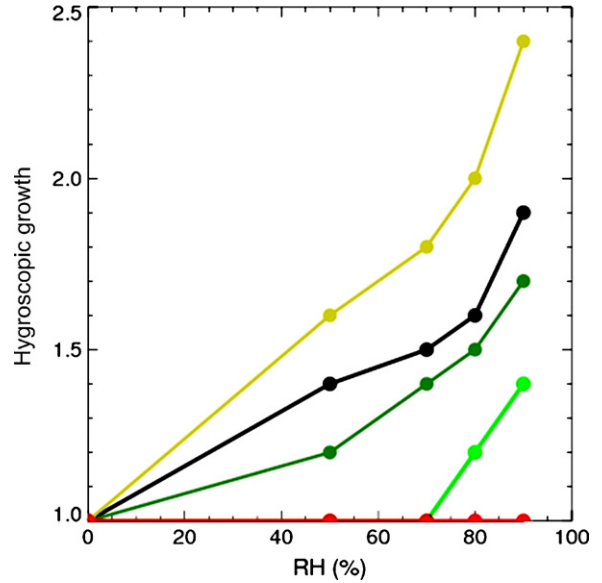


Fig. 6. Hygroscopic growth of aerosol particles as a function of relative humidity (RH) for different aerosols, including sea-salt (yellow), sulfate (black), organic carbon (dark green), carbon black (green), and mineral dust (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

Fig. 5 shows that visibility range varies with aerosol particle size for the same aerosol mass concentrations (e.g. PM₁₀ = 100 μg/m³). For example, when the radius of aerosol particles is smaller than 1 μm, visibility is less than 10 km (poor visibility). Increasing aerosol size (e.g. >1 μm), the visibility is significantly improved while not changing the aerosol mass concentration. This result suggests that size distribution of aerosol particles is a crucial parameter in assessing the impact of aerosols on visibility.

Second, hygroscopic growth of aerosol with water vapor in the atmosphere can significantly affect visibility range. According to Martin, Jacob, Yantosca, Chin, and Ginoux (2003), the hygroscopic growth of aerosol particles depends strongly upon the composition of aerosols as shown in Fig. 6. The size of aerosol particles grows rapidly under high relative humidity (RH), the growth rate being strongly dependent upon aerosol composition. For example, with a relative humidity (RH) of 50%, the particle sizes increase by 60%, 35%, 20%, 0, and 0 for sea-salt, sulfate, organic carbon, black carbon, and dust, respectively. With relative humidity (RH) of 80%, the particle sizes increase by 100%, 55%, 50%, 20%, and 0 for sea-salt, sulfate, organic carbon, carbon black, and dust, respectively. The growth of aerosol particles enhances the scattering of solar radiation, leading to reduction of visibility range. According to Eq. (1), when the size of aerosol particles is increased by a factor of 2, the area of aerosols is increased by a factor of 4, thus resulting in the reduction of visibility range also by a factor of 4. For example, under the same aerosol concentrations, if the visibility range is 20 km (a very good visibility) for a dry aerosol, the visibility range could be reduced to 5 km (a very poor visibility) due to the hygroscopic growth of aerosol particles.

Third, aerosol particles can serve as nuclei to induce fog formation. According to the Köhler theory, the growth of aerosol particles to be CCN (cloud condensation nuclei) requires a threshold supersaturation condition S* (RH ~ 100.6%) to reach a threshold particle size of R* (R ~ 0.1 μm) (see Fig. 6.2 of Wallace & Hobbs, 1977). If aerosol particle size (R) is smaller than R*, even though the atmospheric humidity is saturated (RH = 100%), cloud and fog cannot be formed. However, for large aerosol particles with radius R > R*, cloud or fog forms when the atmospheric humidity is saturated. As

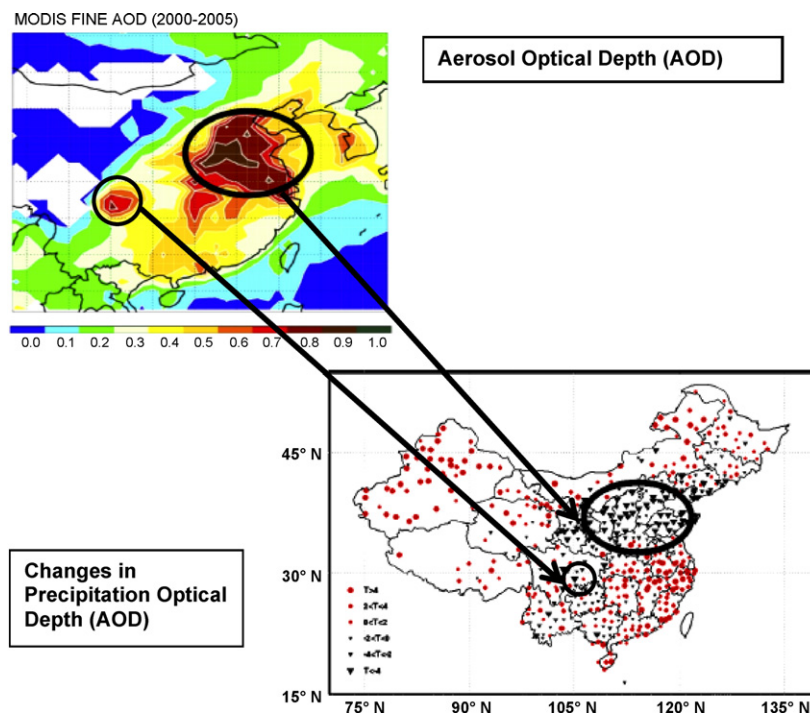


Fig. 7. Correlation between aerosol load and reduction of precipitation in China (Zhao et al., 2006).

a result, with the presence of large aerosol particles (size > 0.1 μm), the occurrence of fog formation is more frequent than without those aerosol particles, causing low visibility and closure of high-ways.

2.3.2. Effect of aerosol pollution on human health

Aerosol pollution affects human health, especially lung and heart diseases. Medical studies showed that exposure to high concentrations of small particles produced by vehicles, industry, and power plants, could raise the likelihood of developing lung cancer (Parent, Rousseau, Boffetta, Cohen, & Siemiatycki, 2007; Pope et al., 2002). Tie et al. (2009) examined long-term records of aerosol particles and lung cancer incidence in the PRD region to infer a statistical relationship between the abundance of atmospheric aerosol particles and the incidence of lung cancer. Their result suggests that the mortality due to lung cancer in the PRD region is closely correlated to the levels of aerosol particles present in the atmosphere near the surface. Since the occurrence of lung cancer requires prolonged exposure to fine particles (Pope et al., 2002), rapid variations in aerosol level cannot cause immediate incidence of the illness. As a result, there is a time lag of about 7-year period between the aerosol trend and the lung cancer mortality trend. Chen, Li, and Zhou (2003) reported a statistical analysis of lung cancer induced by air pollution in the YRD region. They also derived a latent period between lung cancer and exposure to suspended particles of 7 years. Both studies were based upon statistical methods. In the future, more physical/medical studies are needed to examine the impacts of aerosol pollution on human health, through collaboration between environmental and medical scientists.

2.3.3. Effect of aerosol pollution on cloud and precipitation

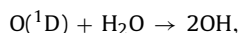
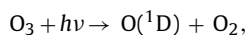
There are more studies on the effect of aerosol particles on cloud formation than on precipitation in China. Zhao, Tie, and Lin (2006) studied a 40-year observation of precipitation trend in China, and correlated this long-term precipitation trend to satellite aerosol data to analyze the relationship between precipitation trend and aerosol pollutions over the CEC region. Their study sug-

gested that there is clear evidence that over eastern central China, marked by the black circles in Fig. 7, precipitation is significantly reduced, the decreasing trend in some areas being larger than 0.4% per year. Compared to the distribution of aerosol, the locations of large reduction of precipitation are closely correlated to the magnitude of aerosol optical depth observed by satellite instrument MODIS (see Fig. 7), which indicates that fine AOD concentrations are high (with maximum of 0.9) over eastern central China, due to heavy industrial emissions, automobile exhaust, and other human induced emission. These analyses also suggested that the frequency of atmospheric instability for cloud formation was reduced in the CEC region during the last 17 years, causing an unfavorable condition for the formation of clouds and precipitation.

3. Potential consequences under low aerosol pollution in the future

As described before, economical development is very rapid in the CEC, YRD, and PRD regions, especially for oil fuel related industrials; e.g. the number of automobiles increased from 0.47 million (1996) to 2.50 million (2007) in Shanghai. To understand the effects of these fast changing economical conditions on environment in China becomes a crucial issue for air pollution control strategy. Reduction of aerosol pollution has many positive effects on improving environmental problems, though not without negative consequences, e.g. enhancement of photochemical activities and ozone production.

According to Tie et al. (2007), ozone (O_3) formation is initiated by the reaction of OH with VOCs/ NO_x /CO. The formation of OH as the key chemical species in controlling the photochemical production of O_3 follows mainly the following reactions:



where $h\nu$ represents photons at UV wavelength. The photochemical production of O_3 is greatly determined by the strength of UV

radiation, and the level of UV radiation can be considered as a “photochemical-limitation” factor for the formation of O₃. The level of UV radiation at the surface of the earth is strongly affected by aerosol load (Martin et al., 2003; Tie et al., 2005). The reduction of aerosol load in the future could lead potentially to high O₃ formation. Because O₃ is a harmful pollutant for human health and crop production, the potential increase in O₃ concentration due to the reduction of aerosol pollution is a negative side-effect. As a matter of fact, during the 1960s, with successful reduction of aerosol pollutions in the US and European countries, O₃ concentrations increase dramatically, e.g. often exceeding 300–400 ppbv in Los Angeles, (often referred to as “Los Angeles Smoggy Event”). On such smoggy days, deaths from heart and respiratory ailments and other diseases arose, causing the death of several thousand more people throughout the United States. Unlike aerosol pollution, which normally takes a long exposure time (a few years) to produce harmful effects on human health (such as lung cancer), a high-ozone day often leads to an increase in risk of acute health the next day, for example, asthma and heart attack. In order to avoid potential O₃ pollution in the future, careful assessment is required for aerosol pollution clean strategy.

4. Summary

Aerosol pollution is briefly reviewed for eastern coast China where many large cities, including 4 mega cities, are located with heavy aerosol load due to their considerable economical development and urbanization in recent years. Satellite observations have revealed that their high aerosol pollution surpasses that in the eastern US. The high aerosol pollution causes wide-ranging consequences on human health, cultivated and natural ecosystems, visibility, weather, and radiative forcing. Several crucial issues regarding the impact of aerosols on environment in these regions are discussed, including their impacts on visibility, fog formation, cloud and precipitation, and human health, especially in the three regions, CEC, YRD, and PRD. The possible consequences for the enhancement of O₃ concentration due to reduction of aerosol load in the future are also addressed. Such analyses and discussions on aerosol pollution in eastern coast China are necessary for better understanding pollution control strategy in order to improve aerosol pollution in these regions.

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