Effect of Atmospheric Haze on the Deterioration of Visibility over the Pearl River Delta*

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ABSTRACT

The studies on the effect of atmospheric aerosol on climate and environment are hot issues in the current circle of international science and technology. In recent years the pollution of aerosol is getting worse and worse over the Pearl River Delta. The clouds of aerosol occur all year round, with heavy pollution area located at the western side at the mouth of Pearl River. The haze weather mainly occurs from October to April next year, resulting in visibility deterioration. From the beginning of 1980s, visibility dramatically deteriorated, obviously increasing haze weather, in which there are three big fluctuations, showing the periods of pollutions of dust, sulphate and dust, fine particle from photochemical process and sulphate and dust accompanying with the development of economy respectively. The long-term tendency of visibility caused by fog and light fog does not show a tendency due to human activities or economic development, which mainly shows the interannual and interdecadal variation of climate. The deterioration of visibility has close relation to the fine particles over Pearl River Delta, with half of PM_{10} overpass the limited value set by national second graded standard (150 μg m^{-3}), meanwhile, all values of $PM_{2.5}$ overpass the day-mean limited value of American national standard (65 μg m^{-3}), especially from October to January next year, monthly mean values of $PM_{2.5}$ almost reach two times of standard value, indicating the fine particle concentration is very high. The ratio of $PM_{2.5}$ to PM_{10} is also very high, reaching 58%-77%, higher especially in dry season than in rainy season. Thus it is the fine particle pollution in aerosol pollution over the Pearl River Delta. Compared with the data of 15 years ago, the ratio of fine particle to aerosol has obviously increased.

Key words: Pearl River Delta, aerosol cloud, brownish haze, visibility deterioration

1. Introduction

Due to its global climatic effect, the atmospheric aerosol is one of the important fields that have caused wide concerns in recent years (Penner et al., 2004; Lohmann and Lesins, 2002; Menon et al., 2002). Its environmental effect, i.e., air pollution, is another important issue that relates with the atmospheric aerosol. Air pollution is also a common problem that most of the developing countries are facing during urbanization and industrialization. Being one of the regions with the fastest economic development across the globe in the last 20 years of the 20th century, PRD (Pearl River Delta) is also one of the areas in China in which the aerosol is causing serious air pollution. Having a total area of just more than 8000 km^2, PRD has international metropolitans with population in millions, e.g., Hong Kong, Guangzhou, Shenzhen, Dongguan, Foshan, Macao, and Zhuhai, and dozens of medium-sized cities with population in hundreds of thousands. With large amount of land being exploited on the industrial scale, decreased vegetation, rapidly increased traffic, and vigorously developed township factories and workshops in the region, episodes of air pollution happen so frequently that they have aroused much concern in the government and general public. Air pollution is not only hazardous to the health of inhabitants, but also reduces visibility to pose

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significant impacts on economic activities and livelihood of the citizens, and results in negative impressions of an area or city concerned. As the 2010 Asian Games is going to be held in Guangzhou, it will be badly affected if the current frequent incidents of poor visibility continue. It faces a difficult job of improving the air quality and beautifying urban scenes. Studies on responsible environmental factors and rational measures and proposals for mitigation are so important that they have much to do with coordinated and sustainable development of cities concentrated in the whole area of PRD.

Aerosol particles are those in the solid or liquid form that suspend in the atmosphere with the diameter between 10^{-3} and 10^{1} μm. Though with mass taking up only one billionth of the total mass of the atmosphere, aerosol particles have important contribution to both the radiative transfer of the atmosphere and water cycles (Luo et al., 1998). The ocean, soil, biosphere, and volcanoes are main natural sources of the airborne aerosol particles, which have significant effect on climate change, formation of clouds, variation of visibility, environmental quality, cycles of trace atmospheric elements, and people's health. Since the Industrial Revolution, anthropogenic activities have resulted in direct emission of huge amount of particles and polluting gases into the atmosphere, with the latter transforming to aerosol particles through chemical reaction in the heterogeneous phase.

In 1999, European and American scientists discovered that a 3-km-thick layer of brownish aerosol clouds was always covering the south of Asia and named it "Asian Brownish Clouds" (Ramanathan et al., 2002), which is also known as the weather of haze (Wu, 2005, 2006). It is mainly made up of carbon black, dust, sulphate, ammonium salt, and nitrate. It was later renamed as "atmospheric brownish clouds" when similar phenomena were also found in other continents. It was further suggested that the formally assumed cooling effect due to the radiative forcing by aerosols be corrected to some extent and particularly argued that carbon black in the atmospheric haze played a key role in climate warming (Ramanathan et al., 2002), increasing the uncertainties regarding the contribution of radiative forcing of aerosols to climate change. It appears more urgent to acquire direct observations of the aerosols with high accuracy and temporal-spatial resolution so that China can undertake independent, self-reliant assessment of the climatic and environmental effect of aerosols.

2. Data and method

In this paper, the data of visibility, humidity, and observed weather phenomena are from meteorological observation sites in PRD in 1954-2004, optical thickness information are derived by EOS/MODIS satellites in 2001-2003, and fine particles of aerosols are observed at Panyu, Guangzhou in 2004-2005.

A day can be defined as one with the occurrence of atmospheric haze when daily mean visibility is below 10 km, and daily mean relative humidity is less than 90% in addition to the absence of other factors such as precipitation for causing low visibility. A day can be grouped into one with the occurrence of light fog when daily mean visibility is below 10 km, and daily mean relative humidity is more than 90% in addition to the absence of other factors such as precipitation for causing low visibility (Wu, 2005, 2006).

Using Level-2 products of aerosol optical thickness with a resolution of 10 km×10 km, which are available from the MODIS operational data processing system set up by NASA making use of multispectral high-resolution observations of the earth by MODIS onboard the satellites Terra and Aqua as part of the Earth Observation System (EOS). Li et al. (2004) made detailed comparison with long-term optical thickness of the aerosol in the south of China as observed with solar photometers and concluded that the Level-2 product was at such high accuracy that it was able to capture how aerosols act in regions like the south of China where there was dense vegetation and low visible albedo all the year round.

In our work, the Minivol Portable Air Sampler made by Airmetrics, USA was used to take field observation of the mass concentration of PM_{10} and $PM_{2.5}$ at Panyu, Guangzhou, and the method of membrane sampling and weighing was employed. Simultaneous 24-h sampling was done with two samplers for each of the samples.

3. Long-term trends of variation of regional visibility

From the monthly number of days with haze and a 12-month moving average trend in the area of Guangzhou in the past 50 years (Fig.1a), it is known that visibility has been decreasing so much that the number of days with haze has been rising since the early 1980s. The increase is marked with three major fluctuations. The first one was in the period from early to middle and late 1980s when there was a sharp increase. It is generally believed that it was associated with China's first economic boom of the PRD after the implementation of the reform and opening-up policy. Direct release of atmospheric pollutants led to serious aerosol pollution as environmental protection laws, regulations and measures to protect the environment were at the initial stage. In response to the tightening up of environmental policy in China, aerosol pollution was under control for quite a long time towards the end of 1980s. Owing to measures to remove soot and dust across the PRD, visibility was improved substantially. Afterwards, from 1990 to 1997, the second period of worsening visibility occurred, when the scale of economic development increased resulting in worsening pollution of SO_2 and sulfate particles were superimposed with aerosol particles that were directly released. Again, China undertook a campaign against atmospheric pollution that aimed at controlling acid rain and SO_2, with the PRD being the area that were to cut down on both. Visibility was then much improved during 1998-2000. The third period of worsening visibility is now in effect, which began in 2002. Over the past few years, the transportation industry has been developing rapidly in the PRD which caused photochemical pollution due to automobile exhausts. Together with the aerosol and sulfate particles emitted directly, the region is now in the time of multiple atmospheric pollution. The variation of visibility is also subject to the fluctuation of medium- and long-term weather and climate background, and thus it is a very complicated issue that is difficult to overcome. From long-term variation trends of the number of light fog days (Fig.1b), there is nothing to suggest that there are tendency changes that are brought about by mankind activities or economic development. The fluctuations are mainly reflecting those on the interannual and interdecadal scales inherit in the climatic cycle.

Huizhou, a city on the eastern edge of the PRD, is made a point of control. For the PRD, the southeasterlies prevails near the surface in rainy seasons while the northeasterlies is the main airflow in dry seasons, making the city in a windward location of the region most of the time. It is known from Fig.2 that whether there is haze or light fog, Huizhou is free from any tendency changes that are brought about by mankind activities or economic development, and the fluctuations are mainly reflecting those on the interannual and interdecadal scales inherit in the climatic cycle. It can be treated as the background level

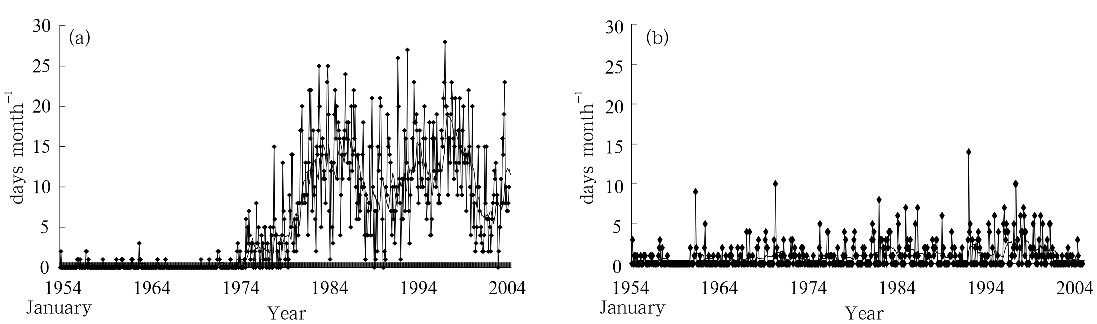

Fig.1. The long-term trend in Guangzhou from 1954 to 2004 (when visibility <10 km and relative humidity <90%). (a) Monthly haze days and (b) monthly mist days.

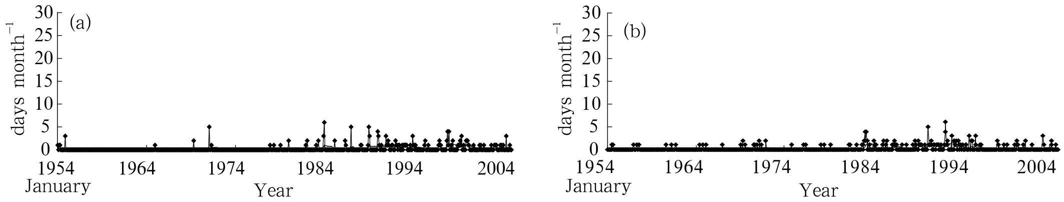

Fig.2. As in Fig.1, but for Huizhou.

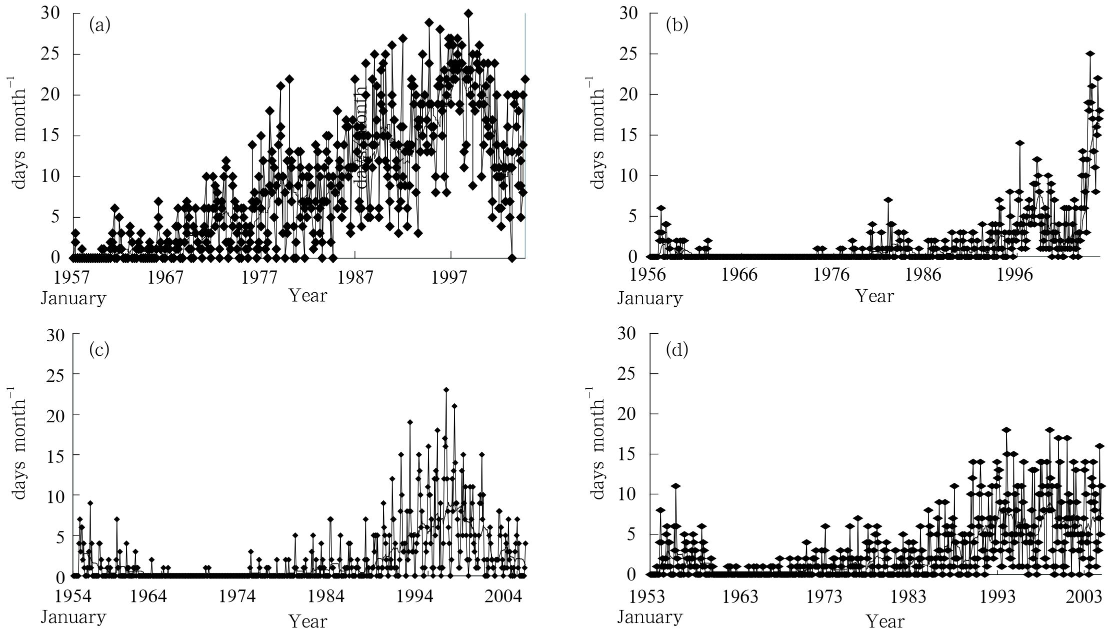

Fig.3. The long-term trend of monthly haze days in Foshan (a), Dongguan (b), Zhongshan (c), and Zhaoqing (d) from 1954 to 2004 (when visibility <10 km and relative humidity <90%).

representative of the variation of visibility in the PRD.

The long-term tendency of visibility variation differs with the location of measuring sites in the PRD. It is known from Fig.3 that the long-term tendency of haze variation in Foshan is similar to that in Guangzhou, for both of them are within the middle of PRD cities. It is also known that there was no significant increase of haze in Dongguan during the first boom of the economy, some signs of increase during the second economic growth though at levels much smaller than that in Guangzhou and Foshan but much more days of haze during the third period of development than the latter two cities, averaging at 15-20 days month^{-1}. The figure reveals an interesting fact about Zhongshan that it did not increase much during the first period, showed comparable degree of rise during the second period with Guangzhou and Foshan, and did not have any tendency to increase during the third period. It deserves further study. Zhaoqing, a city in the lee position of PRD, i.e., inside the tail part of plumes discharging aerosols from the delta all the year round, shows a tendency of steady haze increase, though it does not have any source of aerosols of its own. What should be noted, additionally, is that peak values of haze appeared at the end of 1950s in all of the above cities except Guangzhou. Did it have something to do with the fact that the Chinese people were then mobilized to make steel across every part of the country, with iron and steel works in large cities but substandard furnaces in all other medium and small cities and countryside? It remains to be studied in detail. Likewise, it is known from Fig.4 that light fog does not show any long-term trends of variation for the four cities, indicating that there are not any

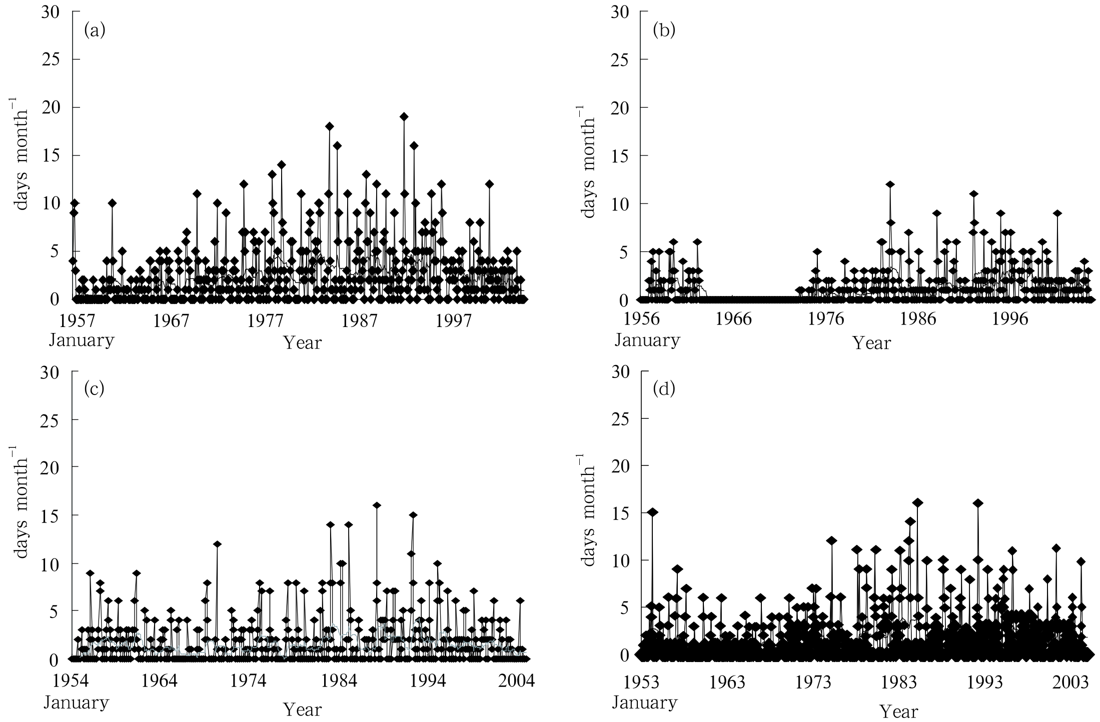

Fig.4. As in Fig.3, but for monthly mist days.

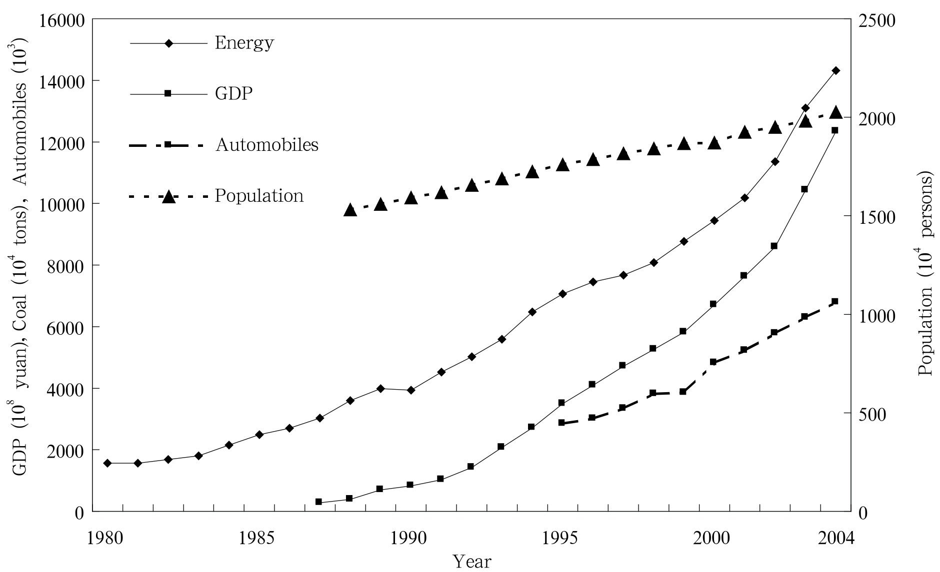

Fig.5. The variation of energy consuming (10^4 tons coal), GDP (100 million yuan), population (10^4 persons), and automobiles (10^3) in seven cities of PRD from 1980 to 2004.

tendency changes that are brought about by mankind activities or economic development and the fluctuations are mainly reflecting those on the interannual and interdecadal scales inherit in the climatic cycle.

The worsening of visibility in the region of PRD is closely related with its rapid expansion of economic capacity. Figure 5 illustrates the energy consumption, GDP, population, and growth of automobiles in seven cities in the PRD (Bureau of Statistics of Guangdong Province, 1981-2005). It is seen that the energy consumption and economic scale have been growing rapidly over the past 25 years in the region, and periods of the middle and late 1980s, middle 1990s and early this century have larger growth rate than the rest, corresponding with the time of worsening visibility presented above.

4. Seasonal variation of optical thickness of regional aerosols suggesting worsening pollution by aerosols in the PRD

In recent years, the aerosol pollution is getting more and more serious and atmospheric transparency is steadily decreasing over the PRD, which has close relationships with mankind activities and economic development and shows significant regional characteristics. Figure 6 gives the seasonally averaged distribution of optical thickness of aerosols for PRD in 2001-2004 remotely sensed by the EOS/MODIS. It shows that the pollution by atmospheric aerosols is much worse over the densely situated cities inside the region than those outside it − the mean optical thickness of 550 nm ranges from 0.7 to 1.2, almost twice as much as that in the periphery areas. Clouds of aerosols, known as brownish haze, are a long-existing phenomenon here. It is the most serious in the western part of PRD west of the Pearl River, which is associated with a large number of scattered sources of emission from various processing industries and concentrated regional traffic network. From the seasonal distribution, it is known that the optical thickness of aerosols throughout the whole air column is much larger in the rainy season than that in the dry season. For a number of years, the monthly mean relative humidity (Fig.7) is higher in March-May and June-August than in September-November and December-the following February. It is not, however, the same thing as the horizontal visibility near the surface, suggesting that the optical thickness as measured by satellites does not represent the true condition of aerosol pollution on the surface and need for further exploitation and processing. It is known from Fig.8 that in recent years, the haze weather in Guangzhou has shown a trend that it begins to increase from October and remain at a high level until the following April.

It is also shown in Fig.8 that the number of haze days in the city is 64 days for 2001, 85 days for 2002, 98 days for 2003, and 144 days for 2004. In other words, one out of less than 4 days in 2004 was covered with haze. It is also observed that more days are with haze in dry seasons than in rainy seasons. In an extreme case, there can be as many as 23 days with haze in a month. What the general public complains is mainly the bad visibility, which is well illustrated in Fig.9, in which haze weather is compared with a haze-free view, impressing one with strong contrast of vision.

5. Distribution of fine particles of aerosols

It is known that visibility is associated with the scattering and absorptive capacity of both the particles and gaseous molecules, mainly of the atmospheric particles. If fine particles are processed simply by Reyleigh scattering, then the intensity of scattered light is mainly in inverse proportion with the 4th power of incident light wavelength and directly proportional to the square of particle volume. The volume of the particle has direct linkage with its scale and concentration. For a given wavelength of the incident light and regardless of the effects of chemical composition of gases and particles, the factors that govern the intensity of the scattered light are the scale and concentration of the particle. According to the spectral data of the aerosol observed in good visibility in southern China, the number of particles is about 10^2, 10^4, 10^7, and 10^{11} m^{-3} at 10, 2.5, 1, and 0.1 μm, respectively. The number of giant particles differs from that of submicron particles by 10^9 times ‡. It is then known that the worsening of visibility is mainly associated with fine particles, whose proportion gets even larger when there are episodes of low visibility caused by serious aerosol pollution.

Table 1 gives the monthly mean concentration of PM_{10} and $PM_{2.5}$ observation. It shows that half of the monthly PM_{10} mean values are higher than the limit of daily mean concentration for Level 2 of the Chinese

‡Wu Dui et al., On the macro- and micro-structures of heavy fogs and associated visibility in Mt. Da Yaoshan, Mts. Nanling. (to be published)

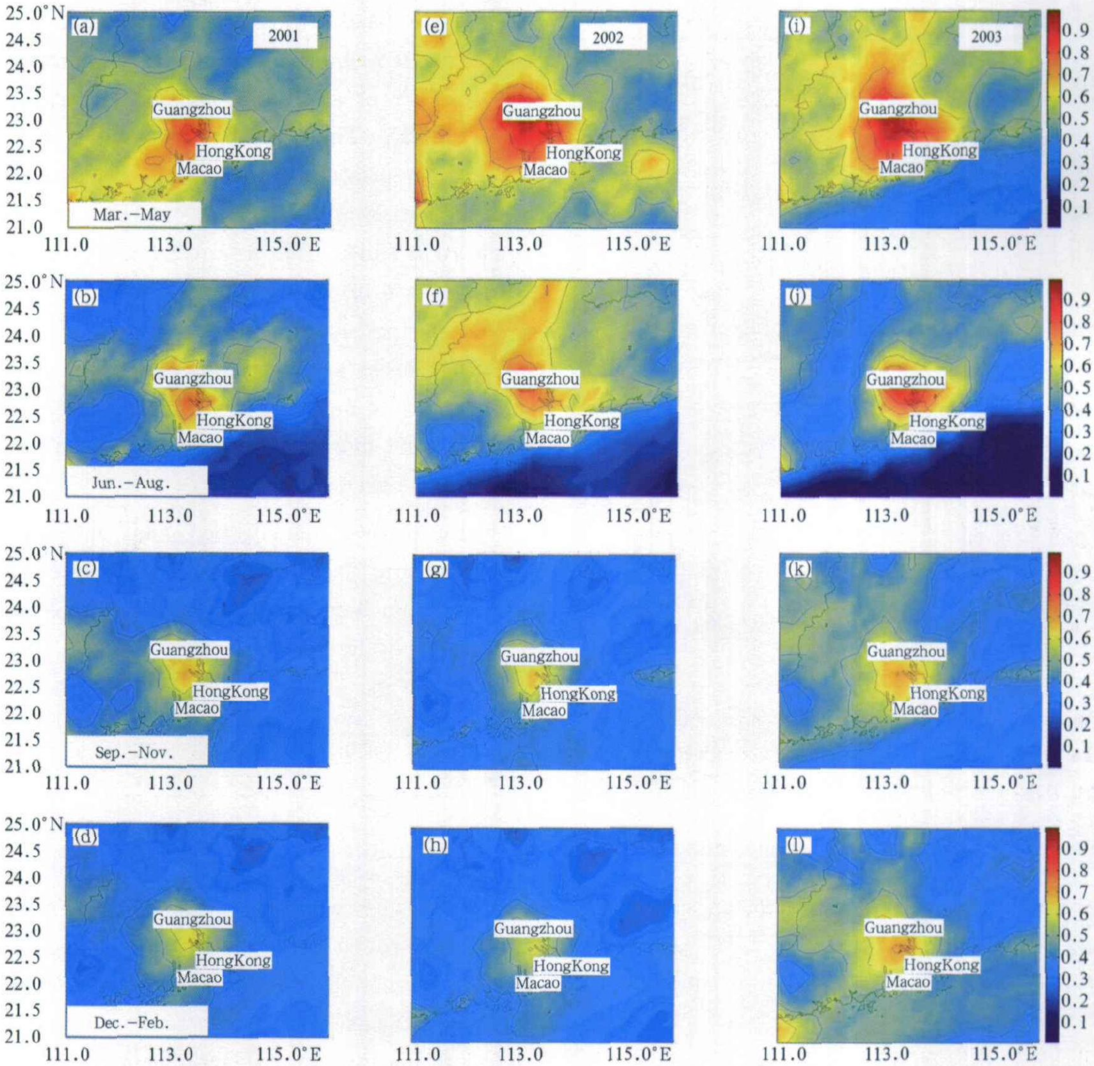

Fig.6. The satellite (EOS/MODIS) measurement of seasonal averaged optical depth of aerosol over PRD from 2001 to 2003.

Fig.9. The photographs of visibility taken in Guangzhou on 17 November (a) and 28 December (b) 2004.

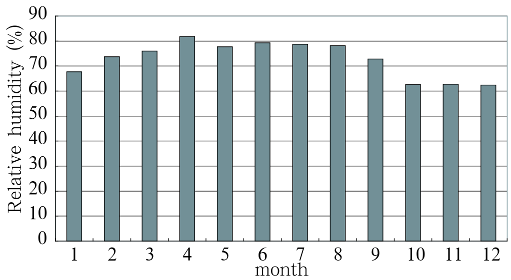

Fig.7. The distribution of monthly averaged relative humidity from 2001 to 2004.

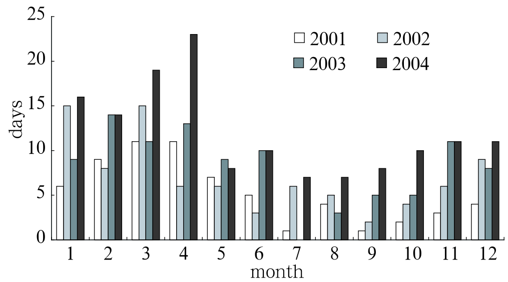

Fig.8. Monthly distribution of haze days in Guangzhou from 2001 to 2004 (visibility <10 km and relative humidity <90%).

Table 1. The mean concentration of aerosols (μg m^{-3}) and the ratio of $PM_{2.5}$ to PM_{10} in Guangzhou

Time	$PM_{2.5}$	PM_{10}	$PM_{2.5}/PM_{10}$
2004-04	69.1	118.2	58.3
2004-05	79.2	115.0	67.0
2004-08	65.2	106.0	62.6
2004-09	82.5	125.2	65.7
2004-10	125.2	211.4	60.8
2004-11	99.5	164.3	61.8
2004-12	100.6	164.9	61.7
2005-01	134.2	174.0	77.9

standard (150 μg m^{-3}) while all of the monthly $PM_{2.5}$ mean values are above the limit of daily mean concentration for the American standard (65 μg m^{-3}), especially, the monthly mean concentration from October to the following January is almost twice as large as the limit, with extremely high concentration of fine particles. In addition, the ratio of $PM_{2.5}$ to PM_{10} is very high (between 58% and 77%), which is higher in the dry than in the rainy season. It shows that the aerosol pollution in the PRD is mainly caused by fine particles, which results in the rapid decrease of visibility in recent years in this region.

The Anderson classification samplers of US were used in the past in most parts of South China to analyze the distribution of mass concentration of the aerosol (Wu et al., 1994; Wu and Chen, 1994; Wu et al., 2001). The threshold with which coarse particles differentiate from fine ones is 2.1 μm, but it is roughly comparable with $PM_{2.5}$ as listed in Table 1. It is shown in Table 2 that from 1989 to 2004-2005, PM_{10} has increased from 117 to 147 μg m^{-3} while fine particles have increased from 54 to 94 μg m^{-3}, if only the suburban areas are compared. It is also shown that the increase of fine particles is much larger than that of PM_{10} and fine particles have expanded their ratio to aerosols over 15 yr.

Table 2. Mean concentration of fine and coarse aerosol particles (μg m^{-3}) and the ratio of fine to coarse particles in Guangzhou during the two periods of 1989 and 2004-2005, respectively

Time	Sampling site	Fine particles	PM_{10}	Fine particles $/PM_{10}$
1989	suburb	54.8	117.0	46.8
2004-2005	suburb	94.4	147.4	64.1

6. Conclusions

(1) Visibility was very good during the period from 1954 to 1978 in the PRD, with less than 40 haze days annually, in which visibility was below 10 km. Since the early 1980s, however, visibility has been deteriorating rapidly with significant increase of haze weather and as many as 200 days in 1997. It is closely associated with the increase of economic capacity of the region. The long-term trend of visibility variation caused by fog or light fog does not show evidences that are brought about by mankind activities or economic development. The fluctuations are mainly reflecting those on the interannual and interdecadal scales inherit in the climatic cycle.

(2) In recent years, the worsening aerosol pollution and atmospheric transparency in the PRD is closely related with mankind activities and economic development, with significant regional characteristics. There are always aerosol clouds over the PRD and areas of high concentration are over the western part of the PRD west of the estuary of the Pearl River. Haze weather mainly occurs from October to the following

April.

(3) The worsening of visibility in the PRD is mainly linked with fine particles. Half of the monthly PM_{10} mean values are higher than the limit of daily mean concentration for Level 2 of the Chinese standard (150 μg m^{-3}) while all of the monthly $PM_{2.5}$ mean values are above the limit of daily mean concentration for the American standard (65 μg m^{-3}), especially, the monthly mean concentration from October to the following January is almost twice as large as the limit, with extremely high concentration of fine particles. In addition, the ratio of $PM_{2.5}$ to PM_{10} is very high (between 58% and 77%), which is higher in the dry than in the rainy season. It shows that the aerosol pollution in the PRD is mainly caused by fine particles, which results in the rapid decrease of visibility in recent years in this region.

(4) Compared with data over 15 years ago, there is a significant increase of the ratio of fine particles to aerosols.

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