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Emerging Air Pollution Issues in Changing Pearl River Delta of South China

Mang Lin[1], Iat-Neng Chan[2], Chuen-Yu Chan[*1],
Xue-Mei Wang[1] and Han-Ying Dong[1]
[1]School of Environmental Science and Engineering, Sun Yat-sen University
[2]Faculty of Science and Technology, University of Macao
P.R. China

1. Introduction

1.1 Background

The Pearl River Delta (PRD) in Southern China is one of the most developed regions in China. Administratively, the delta region is constituted by nine cities in Guangdong Province, and the Special Administrative Regions of Hong Kong and Macao. The PRD has developed into a manufacturing center of the world since the onset of China's economic reform in the late 1970's. The important role of this region in China is highlighted by the high percentage contribution of gross domestic product (GDP) of Guangdong Province, which is mostly contributed by the PRD cities in the mainland, to that of the nation (>10%, National Bureau of Statistics China, 2009).

As an important manufacturing center and city cluster, the PRD region is inevitably affected by severe air pollution problems, which attract much public attention. In response to this situation, a regional air quality monitoring network compositing of 16 automatic stations has been established by the joint effort from Guangdong and Hong Kong governments since late 2005 with an aim to examine the air pollution problem of the region (GDEPMC & HKEPD, 2005). A series of large scale research programs including comprehensive aircraft and ground-base measurements and modeling exercises have been conducted by the scientific community to better characterize and analyse the problem and to find scientific evidence for formulating possible control strategies (e.g. the Program of Regional Integrated Experiments on Air Quality over the PRD of China-PRIDE-PRD in 2004 and 2006) (Zhang et al., 2008; Hua et al., 2008).

1.2 Changing characteristics of the PRD region

Fig. 1 depicts the land use change of the PRD from 1992 to 2004. The major urban areas were mainly found in the capital Guangzhou and the former British colony Hong Kong in the early 1990's. However, in the 21st century, almost the whole PRD region was characterized by urban areas. This dramatic urban expansion was found to be one of the most key factors affecting the air quality and climate of the region (Wang et al., 2007; Kaufmann et al., 2007). Furthermore, the steady increasing trends of GDP and electricity consumption also

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[*]corresponding author

highlight the tremendous progress of urbanization and industrialization of this region (Fig. 2). Concurrent atmospheric composition changes and air quality degradation have been observed by space-borne satellite (e.g., Richter et al., 2005; Van der A et al., 2006; Ghude et al., 2009) and limited long-term ground-based measurements. Chan et al. (2004) first deduced that the regional background ozone (O_3) concentration in south China including the PRD region had been increased at a rate of 1.5% per year from 1984 to 1999 based on the urban measurements in Hong Kong. This finding was recently proven by Wang et al. (2009) using the data recorded from a background station in Hong Kong during the period 1994 to 2007. Besides, the metropolitan Guangzhou was also inevitably suffered from the air quality and visibility degradation during recent half century (Deng et al., 2008). The China's "12th five-year's plan" intends the PRD to transform its labor intensive and resource consuming light industry to heavy industry, telecom, equipment manufacture, auto and petrochemical industries for examples. With such a strategy, the traditional industry and enterprises are forced to move out from this region. Moreover, "cleaner" fuels such as liquefied petroleum gas (LPG) and low sulfur gasoline have been promoted by the government. Such massive changes of industry structure and prevalent fuel are anticipated to have strong effects on air quality. For instance, Tang et al. (2008) reported that there have been around 1.5 times increases in propane concentration in Guangzhou due to the introduction of LPG to the city in 2003. This pilot study highlights the scientific importance of clear understanding of the emerging air pollution issues along with these economic and industrial changes.

1.3 Aim and objectives

The objective of this chapter is to unveil the long-term air pollution changes in three typical commercial and industrial cities of the PRD region, Hong Kong, Macao and Foshan. The possible impacts of these changes on the atmospheric environment and their implications on the regional and urban air quality control strategy will be discussed. These cities are selected simply because they are the cities that we have accessible data. Hong Kong and Macao are located at the southern part of the PRD (Fig. 1). With the second-largest stock market in Asia, Hong Kong is well-known as an international financial center, while Macao is famous as a gambling city with flourishing tourism. On the other hand, Foshan is located at the central-western of the region, where urbanization process is most rapid (Fig. 1). This city is highly industrialized as reflected by its high industrial production value compared with those of Hong Kong and Macao (Table 1). The city is especially famous for ceramic industry, which produced approximately one fourth of the world's ceramic products in 2007 (Peng 2007; Yin 2008). A statistical summary on the general information of these three cities and data available periods are shown in Table 1.

2. Air pollution patterns and occurrence of episodes

Fig. 3 and Fig. 4 summarize the mean concentrations of major air pollutants and the occurrence of episode days in Hong Kong, Macao and Foshan. As expected, the highest SO_2 and PM_{10} concentrations were found in the industrial city Foshan due to the high SO_2 and PM_{10} emissions from industrial activities. Note that the average SO_2 concentration (60 µg m^{-3}) reached the National Ambient Air Quality Standard (Level II) (GB3095-1996) (NAAQS II) of 60 µg m^{-3} (monthly mean). In fact, more than 50% of the days during the period 2001-2007 in Foshan had daily SO_2 concentrations exceeding the NAAQS I of 50 µg m^{-3} (Table 2 and Fig. 4). Besides, the high percentages of PM_{10} episode days in Foshan highlight the severe

	Hong Kong	Macao	Foshan
Population[a]	7.0 million	0.5 million	5.7 million
Area[a]	1100 km²	21 km²	3800 km²
Vehicle number[a]	0.70 million	0.18 million	0.60 million
Value of industrial production[b]	160 billion (HKD)	16 billion (MOP)	940 billion (CNY)
Visibility data	1968.01-2008.12	1990.01-2007.12	1998.01-2008.12
SO$_2$ data	1984.01-2008.12	1998.04-2007.12	2001.01-2008.12
NO$_2$ data	1984.01-2008.12	1998.04-2007.12	2001.01-2008.12
O$_3$ data	1984.01-2008.12	1998.04-2007.12	n.a.[c]
PM$_{10}$ data	1993.01-2008.12	1998.04-2007.12	2001.01-2008.12

a. statistical data at 2008; b. statistical data at 2007; c. n.a. stands for data not applicable

Table 1. Summary of the general statistic information and the periods with data available for analysis

particle pollution at this industrial region. Hong Kong and Macao are both commercial cities with limited manufacturing industries. The SO$_2$, PM$_{10}$ and O$_3$ concentrations of Macao were slightly higher, which could be attributed to the fact that Macao is located at the southeast of Hong Kong (Fig. 1). The prevailing northeasterly wind from September to April will carry aged and polluted air from Hong Kong and other PRD cities like Shenzhen and Dongguan to Macao to deteriorate air quality.

The average NO$_2$ concentration was highest in Hong Kong and lowest in Foshan. This result is reasonable as Hong Kong is a commercial city with dense traffic (Table 1), which results in the elevated NO$_x$ emission and ambient NO$_2$ concentration. However, it is noted particularly that the average NO$_2$ concentration of Foshan during the period of 2006-2008 (60 µg m^{-3}, not shown) was higher than that in Hong Kong and Macao, which suggested that the remarkable increases of vehicle number and vehicular emission in Foshan was becoming more important (Wan et al., 2011). Moreover, although the number of episode day with daily NO$_2$ concentration larger than 80 µg m^{-3} (NAAQS I & II) in Foshan was close to that in Macao (~7.3%), the frequency of daily NO$_2$ concentration exceeding 120 µg m^{-3} (NAAQS III) in Foshan was significantly higher than that in Macao (Fig. 3). This fact emphasizes the needs of implementation of stricter NO$_2$ control measures in Foshan.

	Level I	Level II	Level III
SO$_2$ (Daily Mean)	50	150	250
NO$_2$ (Daily Mean)	80	80	120
O$_3$ (Hourly Mean)	120	160	200
PM$_{10}$ (Daily Mean)	50	150	250

Table 2. Summary of the National Ambient Air Quality Standard (GB3095-1996) in China (unit: µg m^{-3})
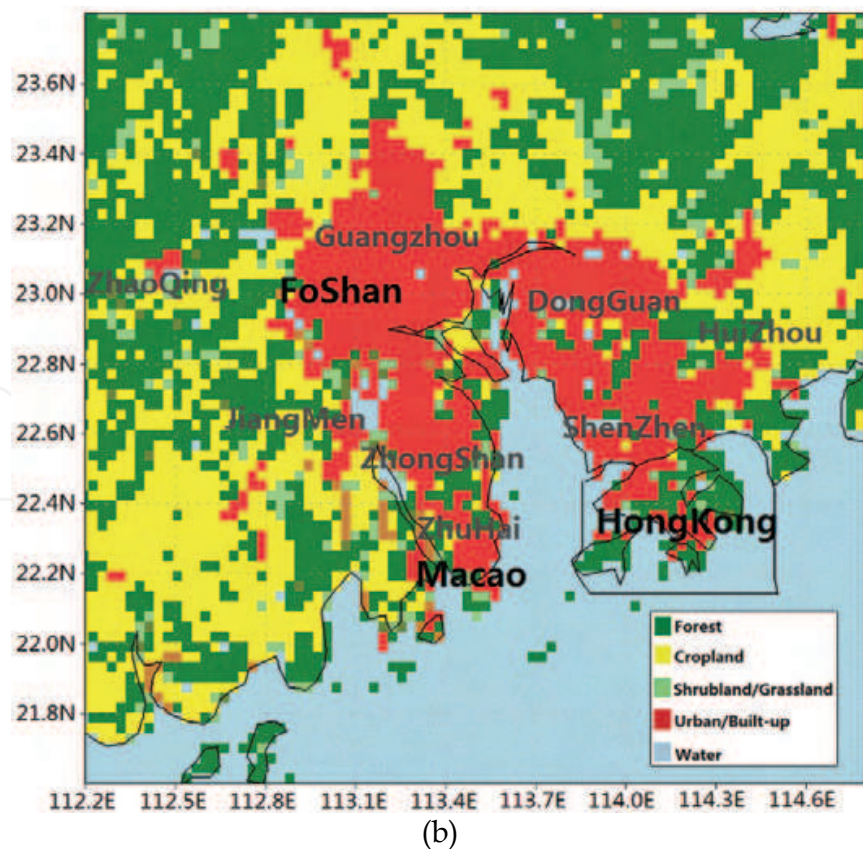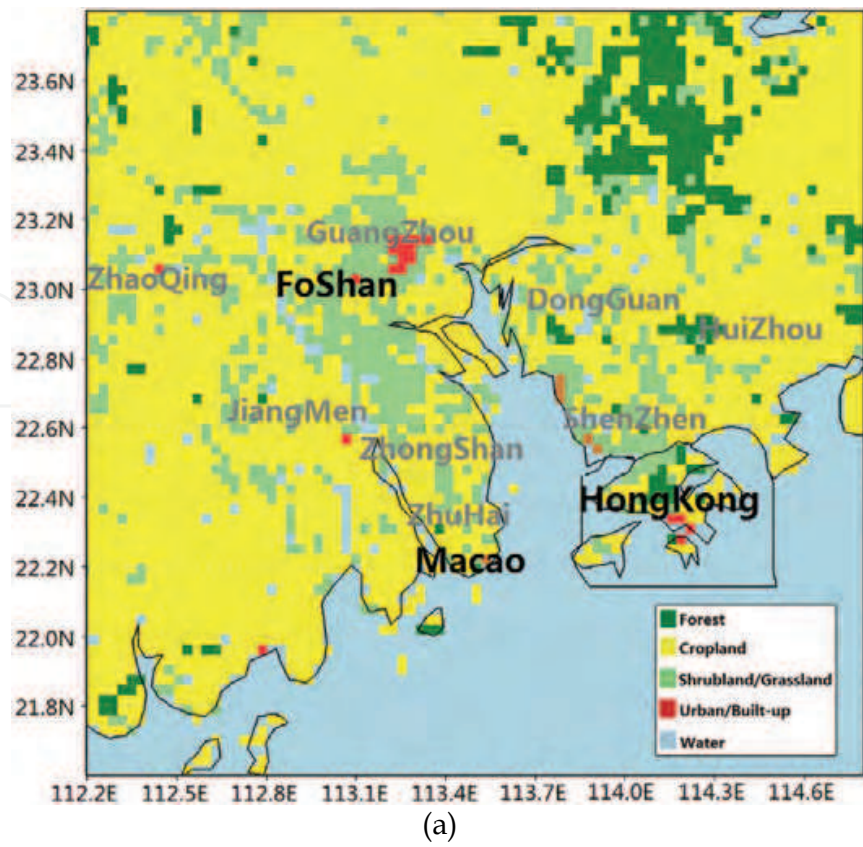
(a)

(b)

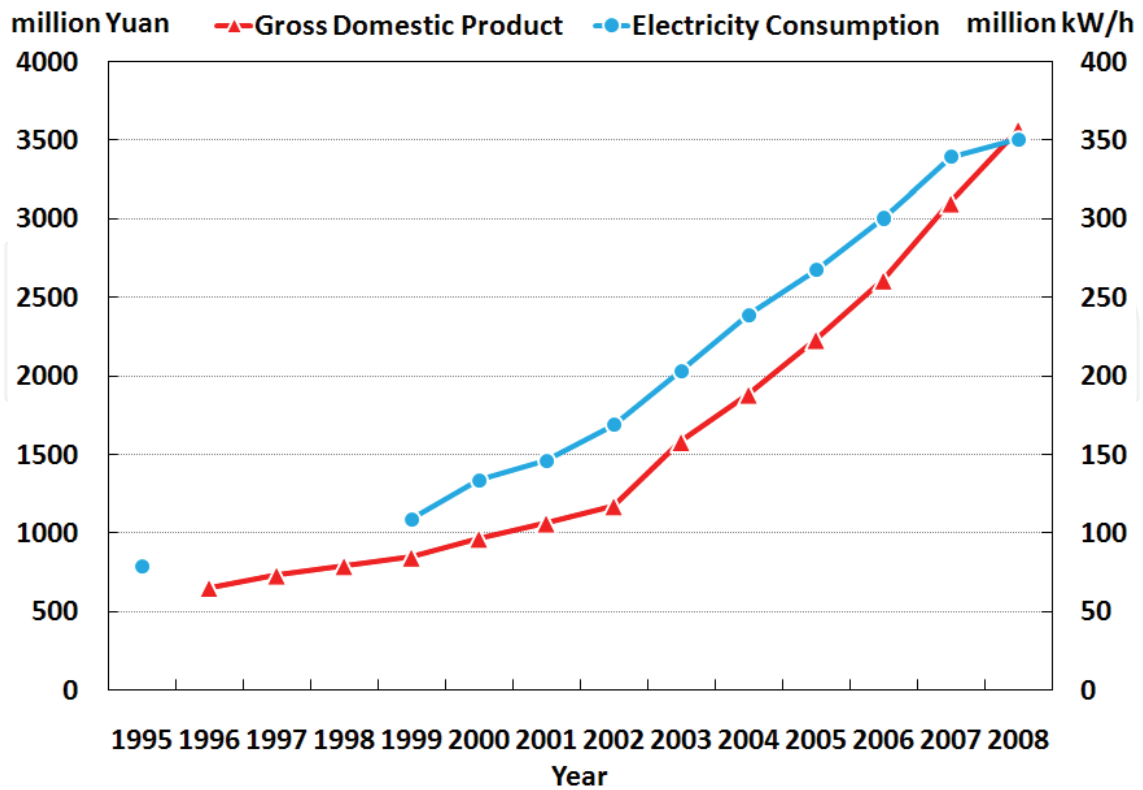Fig. 1. Urban expansion in the PRD region from (a) 1992 to (b) 2004

Fig. 2. Trends of annual gross domestic product and electricity consumption in Guangdong Province from 1995 to 2008.
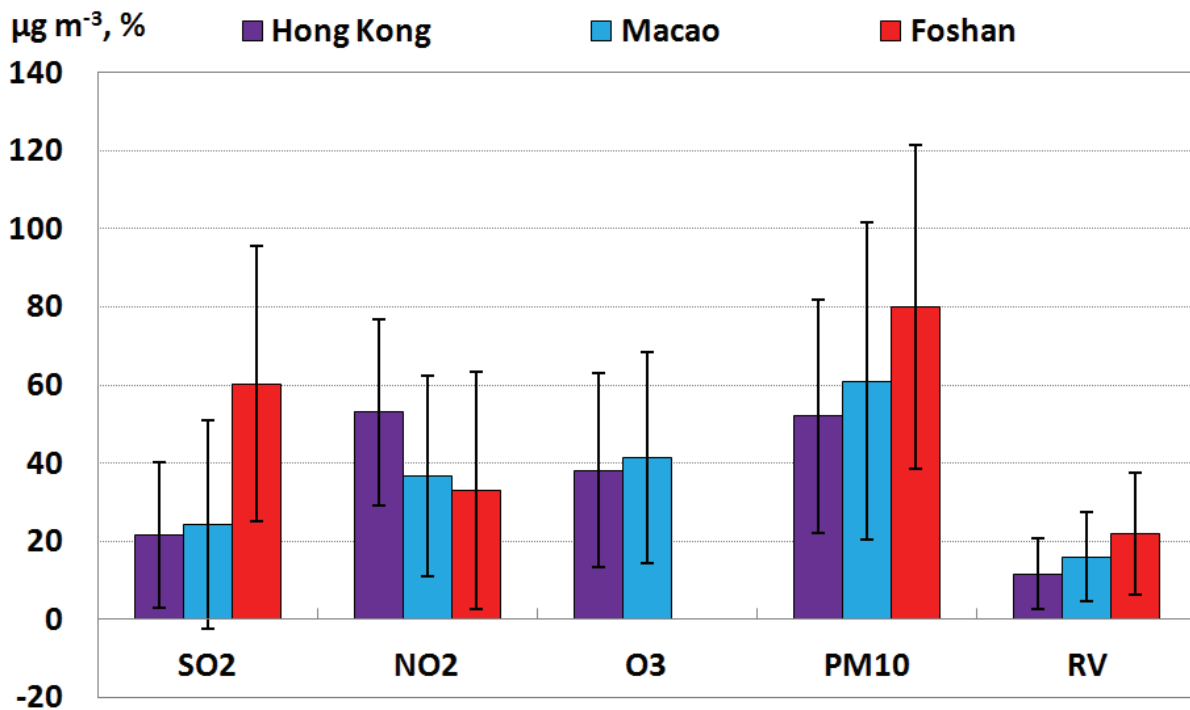

Fig. 3. Comparison of average air pollutants concentrations (2001-2007) and reduced visibility percentage (1998-2007) in Hong Kong, Macao and Foshan (error bars stand for one standard deviation)
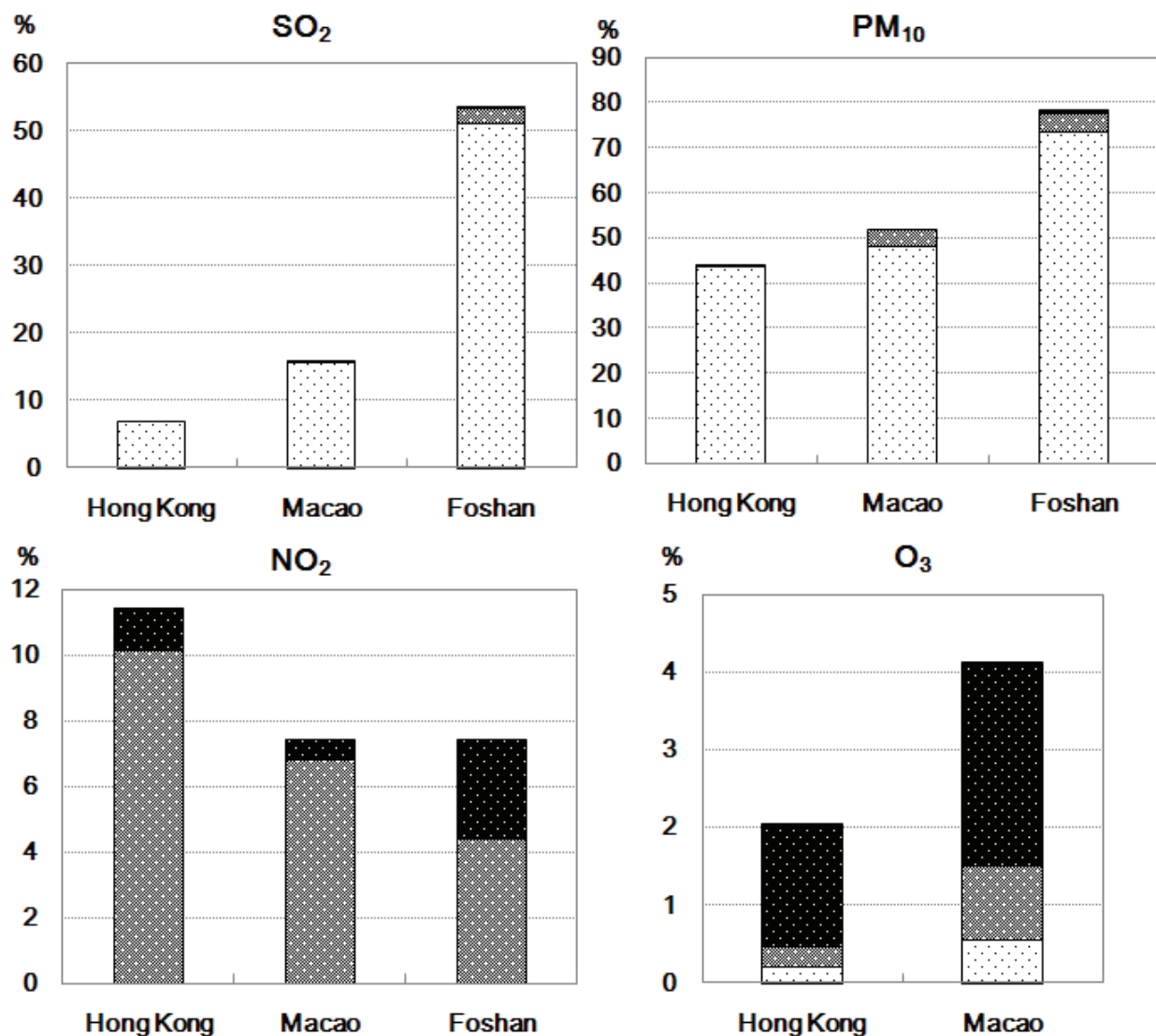
Fig. 4. Comparison of percentages of SO_2, PM_{10} and NO_2 exceeding days as well as O_3 exceeding hours in Hong Kong, Macao and Foshan during the period of 2001-2007 (White, gray and black bars stand for the percentages exceeding NAAQS I, II and III respectively)

3. Changes of major atmospheric compositions

3.1 Surface ozone and nitrogen dioxide

Ozone concentrations in Hong Kong and Macao both showed substantial increases with rates of 1.00 (R^2=0.752) and 1.06 (R^2=0.324) µg m^{-3} per year respectively (Fig. 5). The observed increasing trends are mostly caused by the regional increases in surface O_3 concentrations due to transport of its precursors from south China and East Asia as the urban area of Hong Kong is shown to be a net sink of inflowing O_3 due to the titration effect of nitrogen monoxide freshly emitted from traffic (Chan et al. 2004; Wang et al. 2009). NO_2 concentration in Macao showed a smoothly increasing trend with a rate of 1.26 µg m^{-3} per year (R^2=0.712). We believe that this change is probably accounted by the simultaneous increasing trend of vehicle number in Macao, which increased from 0.11 million in 2000 to 0.18 million in 2007 (Macao Statistics and Census Service, www.dsec.gov.mo). In contrast, NO_2 in Hong Kong kept a rather stable level after the 1990s.

Although long-term O_3 data were not available in Foshan, NO_2 concentration showed sharp increases from 18 µg m^{-3} in mid 2005 to 80 µg m^{-3} in late 2006 contradicting to the general decreases before 2005 (Fig. 5). This increasing rate reached 440% although NO_2 decreased to lower levels from 2007 to 2008. The overall increasing rate during 2001-2008 was 6.34 µg m^{-3} per year (R^2=0.496). The continuous increases in coal burning and road traffic, as well as lack of an efficient NO_2 control strategy, led to the remarkable increases of NO_2 level. More detailed discussions can be found in Wan et al (2011).
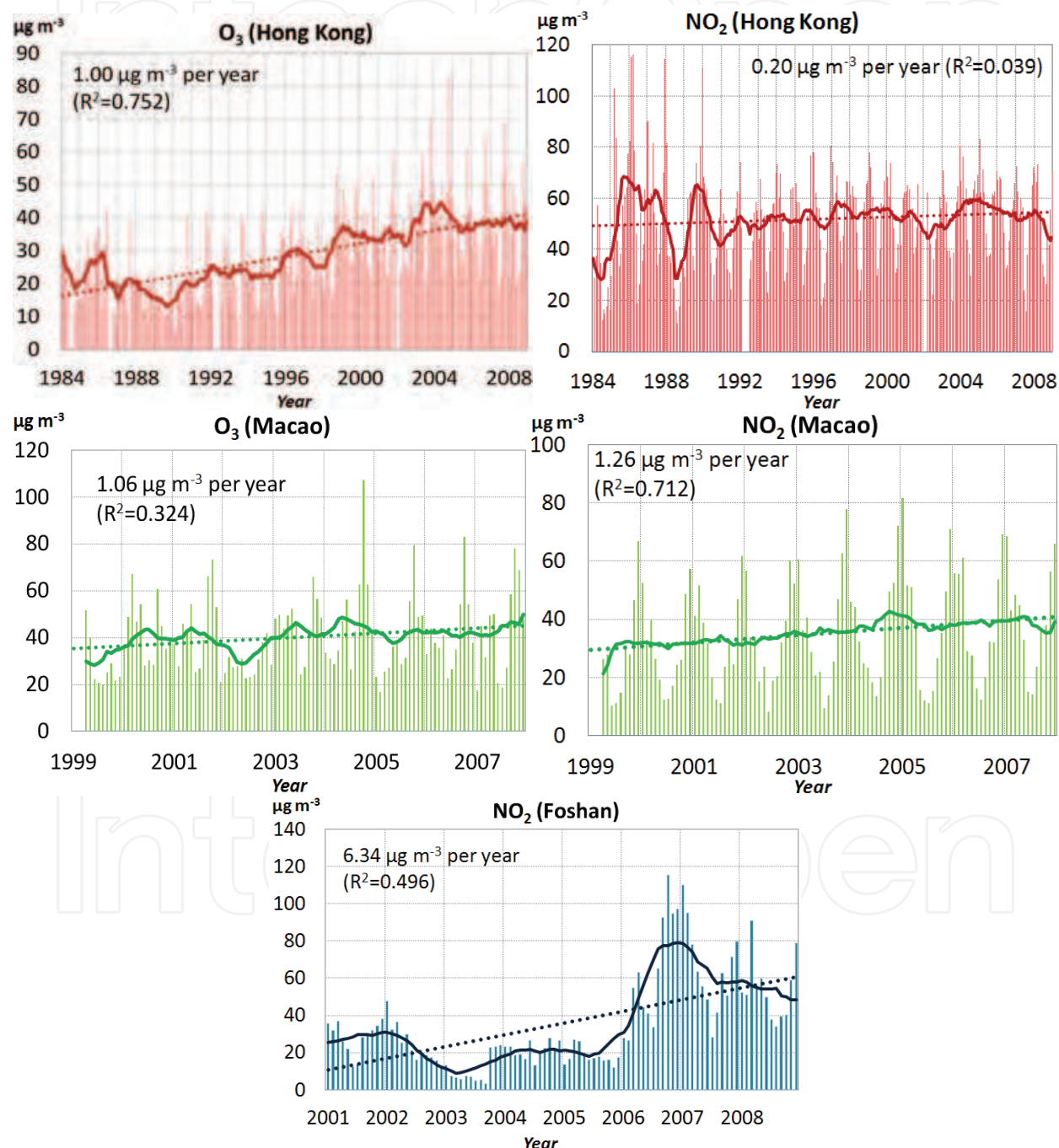

Fig. 5. Trends of O_3 and NO_2 concentrations in Hong Kong, Macao and Foshan (bars indicate the monthly means; solid lines indicate 12 months running averages; dot lines indicate linear regression lines)

3.2 Particulate matter and sulfur dioxide

In Macau, PM_{10} concentrations showed a steady increasing trend with a rate of 2.39 µg m^{-3} per year (R^2=0.716, Fig. 6). As high portion of organic carbon, which is one of the important species in particle primarily emitted by automobile in urban area, was found in PM_{10} in Macao (Wu et al., 2003), the increases of PM_{10} concentration were probably attributed to the increases of vehicle emission as mentioned above. Apart from the local emission, the airborne particulate matter in Macao was also influenced by transported secondary aerosols of regional scale (Wu et al., 2002, 2003). On the contrary, PM_{10} concentrations in Foshan displayed a steady decreasing trend with an overall rate of 3.47 µg m^{-3} per year in 2001-2008, which was believed to be due to continuous implementation of stricter emission control measures on various industrial sources. For instance, many high emitting factories including cement plants and small-scale ceramic plants were forced to close down by the city government in the past decades (Wan et al., 2011).

The SO_2 concentrations in Hong Kong showed a growth rate of 0.28 µg m^{-3} per year in the period of 1984-2008 (Fig. 6). Specifically, the decreases from 1993 were due to the effective banns of high-sulfur fuel usage and reduction of power plant emissions in Hong Kong (HKEPD, www.epd.gov.hk), while the increases in recent years were owing to the increases in SO_2 emissions in both Shenzhen city and Hong Kong (Chan and Yao 2008). Apart from the local SO_2 emission, the increasing trend of regional SO_2 emission also needed to be considered (Lu et al., 2010). Although the SO_2 concentration in Foshan was high when compared to other two commercial cities, a slightly decreasing trend (0.28 µg m^{-3} per year, R^2=0.364) was observed in the 21st century, which was due to the wide application of flue-gas desulfurization (FGD) devices in power plants in response to a new policy of China's government (Lu et al., 2010). In fact, the overall SO_2 removal efficiency of exhaust stream passing the treatment system in various major industrial sectors in Foshan was up to 64% (Fig. 7). However, the continuous growth in coal consumption triggered the substantial increases in 2006 (Wan et al., 2011).

4. Enhancement of atmospheric oxidizing power and its possible impacts

Given that O_3 is a vital atmospheric oxidant and NO_2 is one of the most important O_3 precursors, the remarkable increases of O_3 in Hong Kong and Macao as well as the tremendous augment of NO_2 in Foshan highlight the enhancement of atmospheric oxidizing power in the PRD region. It is reasonable to hypothesize that such changes would exert impacts on atmospheric environmental quality and chemistry. In this section, we used visibility as a proxy of atmospheric environmental quality changes to investigate the impacts of air pollution changes on the atmospheric chemical processes. Following the definition of the Hong Kong Observatory, the observed visibility data were transformed to Reduced Visibility (RV) which is defined as the percentage of hours with visibility below 8 km, excluding the data of rainy days or those affected by fog or high relative humidity (≥95%) (Leung et al., 2004). With this definition, the resulted RV would better indicate the frequency of visibility degradation caused by elevated pollutant level in the atmosphere. As expected, the highest RV was found in Foshan while the lowest RV occurred in Hong Kong (Fig. 3).

Three multiple regression models and the partial correlations between RV and each air pollutant were calculated. The model results were subjected to the F-test and student t-test with a significant level $p<0.05$. After that, the air pollutants with significant partial correlation were kept at the model equations while others were removed from the equations

(Table 3). Generally, visibility in Hong Kong is primarily influenced by concentration levels of O_3, SO_2 and NO_2 in recent 16 years. Particularly, RV would increase 0.28%, 0.27% and 0.15% if concentrations of SO_2, NO_2 and O_3 increase 1 µg m^{-3} respectively. In Macao, the RV was significantly affected by PM_{10} concentration with a value of increasing 0.33% of RV per 1 µg m^{-3} of PM_{10}. Similar relationship exists in Foshan with a value of increasing 0.50% of RV per 1 µg m^{-3} of PM_{10}. Besides, the RV in Foshan correlated with NO_2 concentration with a value of increasing 0.14% of RV per 1 µg m^{-3} of NO_2.
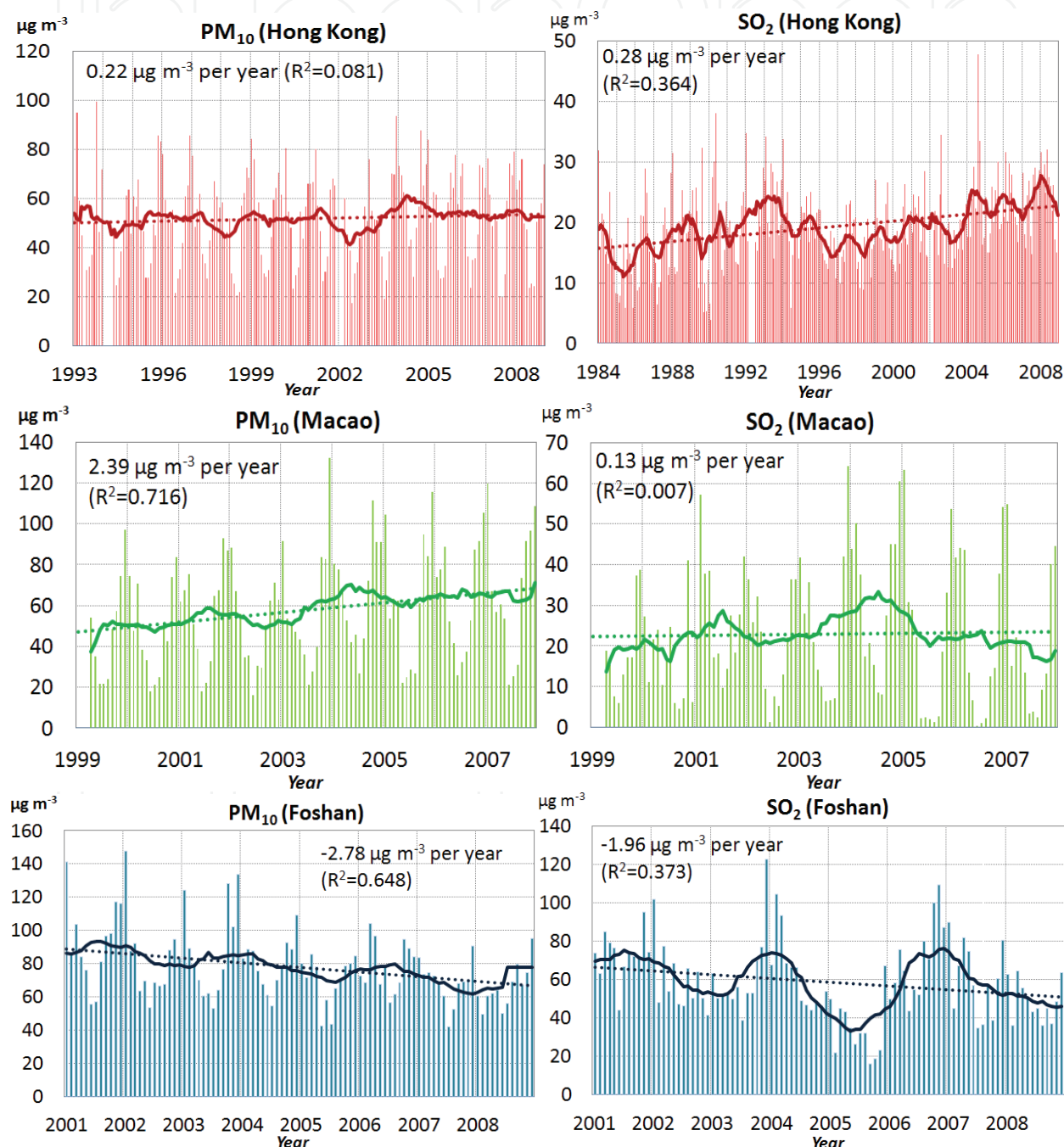

Fig. 6. Trends of PM_{10} and SO_2 concentrations in Hong Kong, Macao and Foshan (bars indicate the monthly means; solid lines indicate 12 months running averages; dot lines indicate linear regression lines)

It is well-known that visibility impairment is always proportion to the loading of fine particles owing to the scattering capacity of aerosol. Besides, NO_2 is another important species in the atmosphere which can degrade visibility due to its strong blue-light-absorbing capacity. Therefore, it is easy to explain the correlation between RV and PM_{10} as well as NO_2.

Regression Model	Independent Variables	Equation[a]
1 (Hong Kong 1993 – 2008)	O_3, SO_2, NO_2, PM_{10}	$[RV] = 0.28 [SO_2] + 0.27 [NO_2] + 0.15 [O_3] – 15.80$
2 (Macao 1999 - 2007)	O_3, SO_2, NO_2, PM_{10}	$[RV] = 0.33 [PM_{10}] – 5.70$
3 (Foshan 2001 - 2008)	SO_2, NO_2, PM_{10}	$[RV] = 0.14 [NO_2] + 0.50 [PM_{10}] - 21.24$

a. Units of RV and air pollutant are % and µg m^{-3}, respectively.

Table 3. Summary of equations calculated by multiple linear regression method
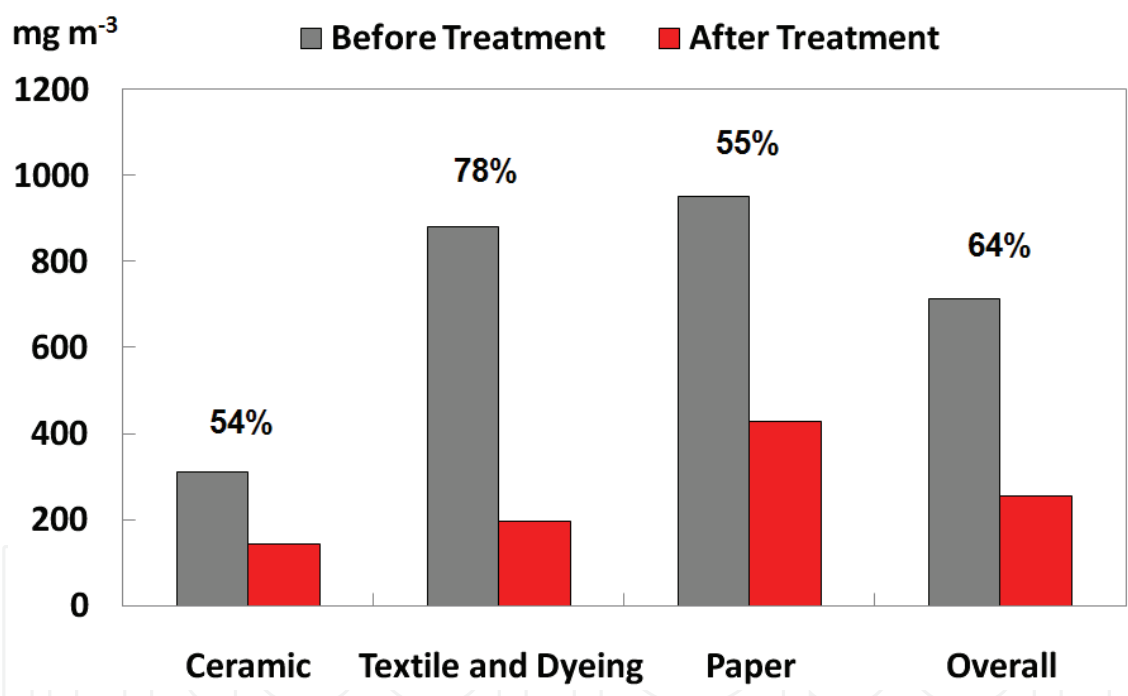

Fig. 7. Emission data of major industrial sectors in 2007 and 2008: comparison of SO_2 concentrations before and after emission control treatment (Source: Wan et al., 2011)

However, the correlation between RV and SO_2 as well as O_3 can hardly be directly interpreted because both O_3 and SO_2 are rather weak in absorbing and scattering visible light, and they thus will not produce strong influence on visibility directly. In fact, this result highlights the changes of atmospheric chemistry due to the tremendous increases of O_3 concentration in Hong Kong and Macao. In the enhanced O_3 atmosphere, the increasing oxidation rate would transform SO_2 to secondary fine sulfate particles more rapidly, which could effectively degrade visibility (Fig. 8, Meng et al. 1997, Shao et al. 2006). The chemical mechanism of S(IV) to S(VI) transformation has been extensively studied in literatures (e.g. Penkett et al, 1979;

Stockwell and Calvert, 1983; Seinfeld and Pandis, 1998; Liang and Jacobson, 1999). The enhanced formation of secondary sulfate in the O_3-rich atmosphere mentioned above actually agrees with the findings from a recent study, in which SO_4^{2-} concentrations in East Asia were found to increase at a greater rate than SO_2 emissions and SO_2 concentrations because "East Asia is a less oxidant-limited area than other parts of the world" (Lu et al. 2010).

In addition, although long-term O_3 data in Foshan were not available, the elevated level of NO_2 concentration more or less highlights the enhancement of oxidizing power of atmosphere in this region as well. It is well known that O_3 is generated from the photolysis of NO_2 and reacts mainly with NO to regenerate NO_2 quickly. If CO or VOCs are present, the simply photostationary state mentioned above is modified in a way that NO_2 can be regenerated through the reaction between NO and HO_2 (or RO_2). Net formation of O_3 occurs because the conversion of NO to NO_2 is accomplished by the HO_2 (or RO_2) radical rather than by O_3 itself. Therefore, the enhanced NO_2 concentration in the atmosphere also reflects the presences of other secondary pollutants like fine particle which significantly contributes to visibility impairment. The significant correlations between RV and NO_2 concentration in Hong Kong and Foshan thus underline the important role of NO_2, or even secondary pollutants, play in visibility reduction. In Macao, RV did not correlate well with O_3 and NO_2 concentrations. However, the high portion of secondary aerosols in PM_{10} and steady increasing trends of O_3 and NO_2 also emphasize the vital role of high O_3 levels play in photochemical formation of secondary pollutants such as sulfate, which would exert notable impacts on visibility, public health and climate.

5. Summary and discussion

Changes of major atmospheric compositions and air pollution levels due to the rapid economic and industrial development have been observed in the PRD region. The data such as those presented in this paper suggest that these long-term air pollution trends have vital implications on the formulation of regional air quality control strategies. Generally, the elevated concentration levels of NO_2 and O_3 in the three commercial and industrial cities highlight the enhancement of atmospheric oxidizing power in the PRD region, which may exert profound effects on atmospheric chemistry, public health as well as regional climate.

Specifically, both of SO_2 and O_3 concentrations in Hong Kong show significant increasing trends. Given that SO_2 would be oxidized to secondary sulfate more easily in the O_3 enhanced atmosphere, the simultaneously increasing O_3 and SO_2 are reasonably expected to trigger the formation of secondary sulfate and resulted in the pronounced visibility degradation. Wang et al. (2009) have suggested that short-term O_3 control strategies should be aimed at O_3 precursor sources in Hong Kong and the adjacent PRD while the long-term ones need to consider distant sources. Given that the increase of SO_2 concentration was due to the enhanced local SO_2 emissions of Hong Kong and Shenzhen (Chan and Yao, 2008) as well as elevated regional SO_2 emissions in East Asia (Lu et al., 2010), similar strategy should be adopted for SO_2 control.

In Macao, the increasing trends of secondary pollutants like O_3 and NO_2 highlight the influences of increasing O_3 precursor emission in its upwind regions such as eastern PRD and the east Chinese coast. Therefore, the air pollution controls of Hong Kong, as well as other upwind regions are vital. Furthermore, the augment of NO_2 concentration also implies

that the local vehicular emission control of Macao should not be neglected. As PM_{10} in Macao was mainly affected by local vehicular emission and regional transport, its increasing trend also emphasized the importance of both local and regional controls.
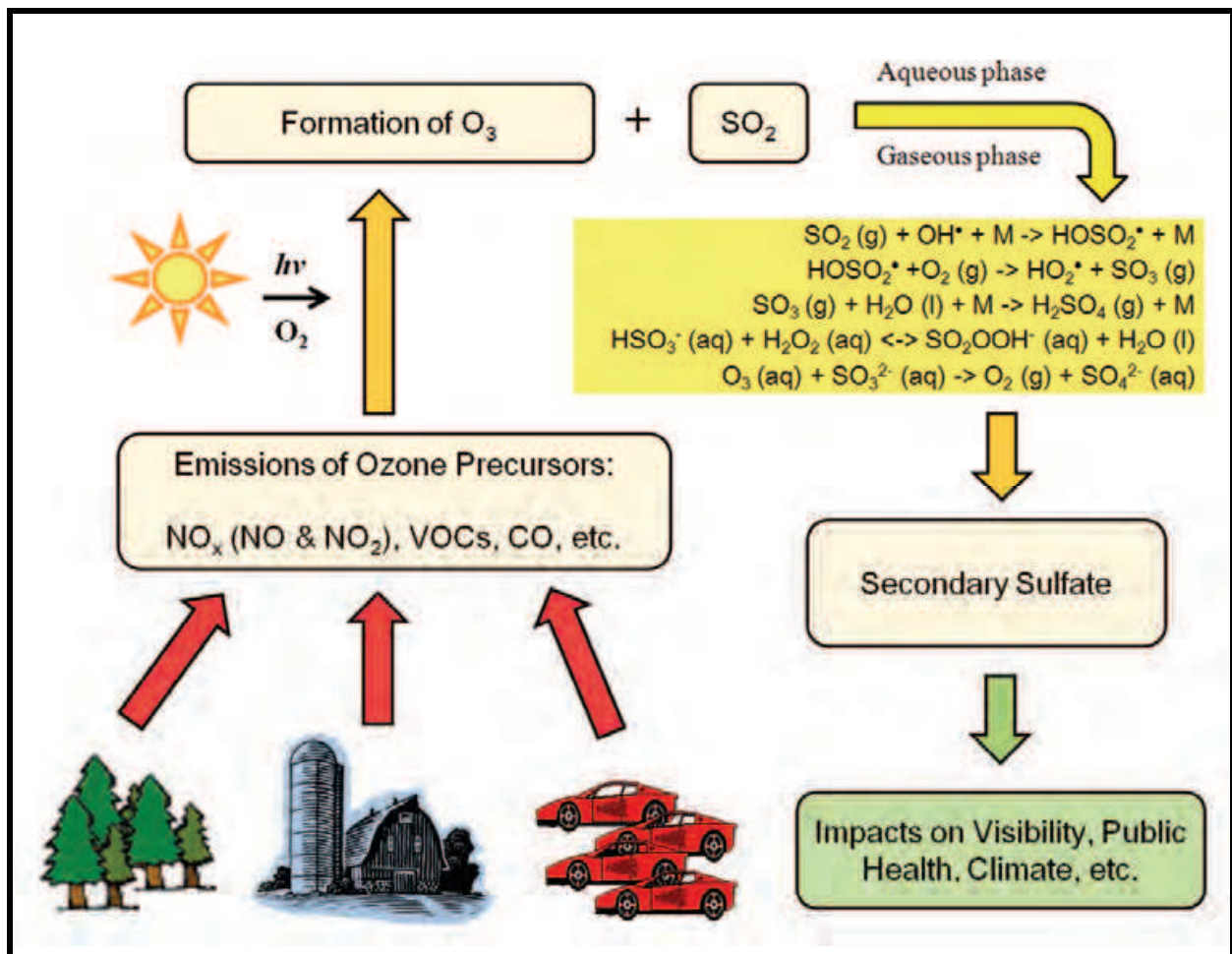

Fig. 8. Schematic diagram showing photochemical ozone formation from its precursors emitted from anthropogenic and natural sources and its impact on secondary sulfate formation and visibility degradation through aqueous and gaseous phase chemical processes in the ozone-enhanced atmosphere.

On the other hand, decreasing trends of PM_{10} and SO_2 were observed in Foshan. These are due to the efforts of more efficient control in industrial sectors. In a recent paper, Wan et al. (2011) emphasized that the implementation of stricter PM_{10} and SO_2 control measures in industrial exhaust had resulted in reduced ambient air pollution level. However, this industrial city is still severely polluted compared to the commercial cities like Hong Kong and Macao due to its high coal burning and industrial emissions. Such fact suggested that the SO_2 as well as particles emission control measures must be strengthened. In contrast, the surprising increases of NO_2 concentration due to the continuous increasing in road traffic and lack of efficient NO_2 control in industrial sectors should be noticed. Such increasing trend is an evident of atmospheric oxidizing power enhancement in this region. If the air quality control strategies are not changed, the NO_2 concentration will keep increasing especially with the fact that the vehicle number keeps on increasing sharply in recent years.

Overall, due to the rapid economical and industrial development, the nature of air pollution in the PRD region has been changing sharply. Essentially, the findings reported in this chapter indicated that the atmospheric oxidizing power in the PRD region has been continuously increasing. Even in the industrial city, which was more affected by primary pollutants like SO_2, the vehicle emission and resulted photochemical pollution should be noticed. The enhancing atmospheric oxidizing power could change the atmospheric chemistry by triggering the secondary pollutant formation via increasing oxidation rate. The increasing secondary pollutants may exert a number of significant impacts on public health and regional climate. As most of secondary pollutants were related to transport of aged air mass, such findings emphasize the critical impacts of trans-boundary transportation and regional air pollutions. With an aim to control the secondary pollutants, cooperation with other provinces and even countries become more and more important. Besides, due to the enhanced atmospheric oxidation capacities, primary pollutants like SO_2 and some of volatile organic compounds will be transformed to secondary fine particles more efficiently, and therefore, stricter implementation of local primary pollutant control was also necessary. In summary, in order to efficiently improve the regional air quality in the PRD region, local and regional efforts on air pollution control are both required.

6. Acknowledgment

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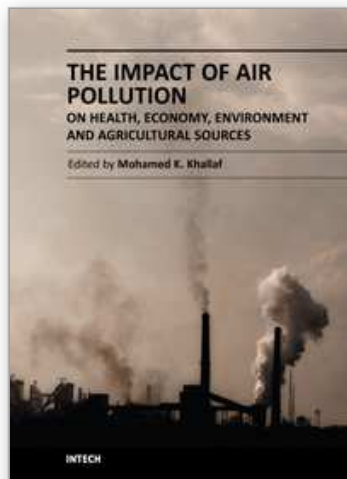
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