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Trends in Air Pollution During 1996 - 2003 and Cross-Border Transport in City Clusters Over the Yangtze River Delta Region of China

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ABSTRACT

Air quality data from city clusters in the fast developing Yangtze River Delta (YRD) region of China during 1996 - 2003 were analyzed, with a cross-border transport study using the Regional Acid Deposition Model System (RegADMS). Investigations show that the annual average concentrations of SO_2, NO_2, PM_{10} are 12 ~ 64 , 13 ~ 57, and 79 ~ 184 $\mu g\ m^{-3}$, respectively. As the primary air pollutants in the target area, surface NO_2 levels increased by 13% while PM_{10} levels decreased by 39% from 1996 to 2003. The surface SO_2 concentration showed fluctuations during the study period, reaching a minimum in 1999 and rising again in 2003. Acid rain still remains an important atmospheric environmental issue. The frequency of acid rain was about 23.5 ~ 36.7%, and the pH value of precipitation ranged from 5.09 to 5.48, with little change in these years. Modeling studies indicated that sulfur deposition and nitrogen deposition were in the ranges 0.5 ~ 10 and 0.2 ~ 5 $g\ m^{-2}\ yr^{-1}$, respectively; these levels exceed the critical load in some regions. The trans-boundary transport of sulfur deposition and nitrogen deposition due to SO_2 and NO_x emission among city clusters (Shanghai and the other 8 cities in Jiangsu Province, including Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Zhenjiang, and Taizhou) in the YRD region was significant. The emission from Shanghai contributes 5% ~ 29% of sulfur deposition and 3% ~ 30% of nitrogen deposition

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in the 8 cities, while the 8 cities contribute 27.5% of sulfur deposition and 20.2% of nitrogen deposition in Shanghai.

(Key words: Air pollution, Acid rain, Yangtze River Delta, China)

1. INTRODUCTION

China has experienced rapid economic growth in the past two decades. As one of the fast developing regions, the Yangtze River Delta (YRD) has suffered from air pollution due to economic expansion which has resulted in an increasing need for energy, thus the consumption of fossil fuels and emissions of major air pollutants (NO_x, SO_2, CO) into the atmosphere (Galloway 1989; Kato and Akimoto 1994; Aardenne et al. 1999; Streets and Waldhoff 2000). Large population, poor resources and strong emissions have caused complex air pollution problems in this whole area, exemplified by severe acid rain, a gradual deterioration in visibility and occasional episodes of high respirable particulate matter, and ozone (Cheung et al. 2001; Wang et al. 2001). Figure 1 shows a map of Yangtze River Delta region and the locations of 9 cities considered in this paper. 8 cities of Jiangsu Province (Nanjing, Wuxi, Changzhou, Suzhou, Nantong, Yangzhou, Zhenjiang, and Taizhou) and Shanghai in the YRD have been included in this acid rain monitoring and control area since 1998 by the National Environment Protection Agency. To understand the air pollution situation in this region, routine automatic monitoring stations were set up by the local environmental protection agency. However, most of these stations are located in urban or suburban areas, few of them are in non-urban areas, and thus the air quality situation in regions far from urban areas and cross-border air pollution transport are poorly understood. For this reason, numerical modeling is necessary to improve our understanding of the causes of air pollution in the YRD and to propose effective control strategies for policy-makers.

The goal of this paper is to investigate air pollution trends in recent years and cross-border transport in city clusters over the YRD region by use of data analysis and modeling. The paper is organized as follows. In section 2, the air quality data and transport model are described briefly. Trends in air pollution and mutual influence on sulfur/nitrogen deposition between city clusters are discussed in section 3. We give a general summary in section 4.

2. DATA AND MODEL DESCRIPTIONS

2.1 Data

Air quality data of the 9 cities during the period 1996 ~ 2003 were collected for the present study. They include ground level concentrations of SO_2, NO_2 and PM_{10}, most of which were measured by automatic air quality monitoring stations with quality assurance and quality control. The detection limits are 0.5 ppb, 0.4 ppb, 0.5 $\mu g\ m^{-3}$ for SO_2, NO_2 and PM_{10}, respectively. Also collected were acid rain data, including pH values of precipitation, frequency of acid rain and concentrations of major ions in rainwater.

Fig. 1. Map of the Yangtze River Delta region and locations of cities considered.

2.2 Model

The Regional Acid Deposition Modeling System (RegADMS) was used in this paper, which consists of two parts, the meoscale model (MM5) and the Nanjing University Regional Acid Deposition Model (NJURADM). The Pennsylvania State University (PSU) and National Center for Atmospheric Research (NCAR) developed the mesoscale model MM5, which was selected in this study for its common use worldwide. NJURADM was applied to simulate air pollutant concentrations and sulfur/nitrogen deposition. Details of the model's structure and performance were presented by Wang et al. (1996, 2000, 2003, 2004, and 2005).

The meteorological data from the output of MM5 was used to drive RegADMS. MM5 was run in a three layer nesting grid system with horizontal grid lengths of 81, 27, and 9 km. There are 10 equidistant levels in the vertical. The pressure at the model top is 100 hPa. Blackadar's high resolution boundary layer scheme, time-dependent boundary condition and deep cumulus convection parameterization were selected in the simulation.

The 9 km domain is set as 405 × 270 km, covering the YRD and its surrounding area, while the 27 km domain covers East China and its surrounding area. The RegADMS was run with two nesting domains of 27 and 9 km. The 27 km domain supplies boundary conditions for the 9 km domain.

3. RESULTS AND DISCUSSIONS

3.1 Current Situation

3.1.1 PM_{10}, NO_2, and SO_2

Table 1 shows that the annual average SO_2 concentrations for the 9 cities in 2003 were between 30 and 54 $\mu g\ m^{-3}$, which do not exceed the national standard Band II for air quality (60 $\mu g\ m^{-3}$). The SO_2 concentration in Wuxi is the highest, with the next being Shanghai and Taizhou. The annual average concentrations of NO_2 for the 9 cities range from 19 to 57 $\mu g\ m^{-3}$, which are below the national standard Band II (80 $\mu g\ m^{-3}$). However, NO_2 concentration is much higher in large cities (Shanghai, Nanjing, Suzhou) with heavy traffic compared to other cities, suggesting that the contribution of transportation on NO_2 concentration is more important. The annual concentrations of PM_{10} vary from 97 to 132 $\mu g\ m^{-3}$. Except for Shanghai, PM_{10} concentrations in the 8 cities of Jiangsu Province reached or exceeded the national standard Band II (100 $\mu g\ m^{-3}$), suggesting more severe particulate pollution in urban areas due to fast developing industry, transportation and construction.

3.1.2 Acid Rain Frequency and pH Values

In 2003, the annual average pH value of precipitation for the 9 cities was 5.16, ranging from 4.73 to 6.08 (see Table 2). The acid rain frequency averaged over the 9 cities is 34.2%.

Table 1. SO_2, NO_2, PM_{10} concentrations in 2003 ($\mu g\ m^{-3}$).

City	SO_2			NO_2			PM_{10}		
	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
Shanghai	-	-	43	-	-	57	-	-	97
Nanjing	1	218	30	1	477	49	5	385	120
Suzhou	1	161	30	1	203	42	3	425	118
Wuxi	2	557	54	3	125	41	7	302	100
Changzhou	1	147	30	1	103	26	19	342	117
Zhenjiang	1	205	36	2	238	30	7	449	108
Nantong	1	210	41	3	167	30	15	383	100
Taizhou	3	343	42	1	105	19	13	479	108
Yangzhou	1	276	41	1	177	30	2	450	132
Average	-	-	39	-	-	36	-	-	111

Table 2. pH and acid rain frequency in 2003.

City	pH	Frequency（%）
Shanghai	5.21	16.7
Nanjing	4.98	55.8
Suzhou	4.98	40.3
Wuxi	5.27	44.5
Changzhou	4.94	27.4
Zhenjiang	5.42	9.4
Nantong	4.73	62.4
Taizhou	6.08	3.4
Yangzhou	4.84	48.1
Average	5.16	34.2

Here, acid rain frequency is defined as the percentage of day when pH is less than 5.6, with $pH = 5.6$ being the unpolluted value for rainwater. The lowest pH (4.73) and highest acid rain frequency (62.4%) occurred at Nantong, with the next being Nanjing, Yangzhou, Wuxi and Suzhou, with frequencies above 40%. Monitoring data in recent years show that the pH value of acid rain in the Yangtze River Delta region kept fluctuating. Generally, in this region, acid rain problems are more serious than in other regions of China, especially in Nantong and Yangzhou.

3.1.3 Chemical Composition of Rainwater

The concentrations of major anions and cations in precipitation are listed in Table 3. It shows that SO_4^{2-} and NO_3^- are dominant compared to other anions and NH_4^+ and Ca^{2+} are dominant compared to other cations. The high concentrations of SO_4^{2-} and NO_3^- correspond with high concentrations of SO_2 and NO_2, indicating that the precursors of acid rain are SO_2 and NO_2, which are mainly emitted from industry and transportation. The concentration of SO_4^{2-} is high in Wuxi and Taizhou, while NO_3^- concentration is high in Suzhou and Nanjing, showing the relative contribution of SO_2 and NO_2 on acid rain formation in different areas. For Wuxi and Taizhou, high SO_4^{2-} concentration in rain water means the important contribution of industrial sources to acid rain. For Suzhou and Nanjing, the contribution of transportation may also play an important role. The concentrations of Na^+, K^+, Mg^{2+} and Cl^-, F^- are relatively lower, showing that sea salt is not very important in the study region. The NH_4^+ and Ca^{2+} concentrations are relatively higher, suggesting contributions from agricultural activities and soil dust.

Table 3. Chemical composition of precipitation in 2003 (μ eq L^{-1}).

City	SO_4^{2-}	NO_3^-	F^-	Cl^-	NH_4^+	Ca^{2+}	Mg^{2+}	Na^+	K^+
Shanghai	-	-	-	-	-	-	-	-	-
Nanjing	240.9	79.8	9.3	37.6	157.3	171.7	18.6	9.7	8.4
Suzhou	272.3	96.2	10.9	40.4	110.4	318.6	23.3	12.1	23.7
Wuxi	576.6	68.5	18.9	63.1	144.0	373.6	32.6	17.0	12.7
Changzhou	94.8	19.7	11.0	43.3	80.6	120.4	9.7	5.1	4.5
Zhenjiang	189.4	45.5	10.5	30.9	108.5	102.9	15.5	8.1	22.3
Nantong	140.9	37.4	19.2	19.8	135.6	73.0	10.2	5.3	10.2
Taizhou	295.2	58.1	31.0	52.8	24.2	241.7	39.8	20.8	23.6
Yangzhou	105.9	34.5	19.2	22.8	67.3	109.8	12.4	6.5	13.7
Average	239.5	55.0	16.3	38.8	103.5	189.0	20.3	10.6	14.9

3.2 Trends

3.2.1 PM_{10}, NO_2, and SO_2

The annual surface PM_{10}, NO_2 and SO_2 concentrations averaged over the 9 cities are illustrated in Fig. 2. In the figure, a significant decrease in PM_{10} and stable increase in NO_2 are found, while SO_2 shows a gradual reduction before 1999 and rises again after that. For the 9 cities, the annual average concentration of PM_{10} was 79 ~ 184 μg m^{-3}. PM_{10} levels averaged over these cities decreased 39% from 1996 (181 μg m^{-3}) to 2003 (111 μg m^{-3}). Although the PM_{10} level declined in the 8-year period, it still exceeded the China Air Quality Standard (CAQS) Band II (annual average 100 μg m^{-3}) throughout most of the period considered, which means that particulate matter is still an important factor in air quality of the YRD region. The significant negative trend in PM_{10} concentration during 1996 - 2003 suggests that control of particulate matter in recent years has been successful.

The annual average SO_2 concentration of the 9 cities ranges from 12 to 64 μg m^{-3}. These values, except for those of Changzhou and Wuxi, were all below the CAQS Band II (60 μg m^{-3}) post 2000. SO_2 levels averaged over these cities peaked in 1997 (48 μg m^{-3}) and reached a minimum in 2000 (32 μg m^{-3}). SO_2 concentration remained large in 2001 and 2002 (46 μg m^{-3}) and decreased in 2003 (38 μg m^{-3}).

The range of annual average NO_2 concentrations for the 9 cities is 13 ~ 57 μg m^{-3}, which increased 13% from 1996 (29.5 μg m^{-3}) to 2003 (33.3 μg m^{-3}). The current NO_2 level is below the CAQS Band II (80 μg m^{-3}). However, it is apparent that these values are going up steadily because of expansion and urbanization in these cities, which mainly results from increased vehicle usage and associated end gases (NO_2, VOC, CO etc.).

Fig. 2. The variations of average concentrations of PM_{10}, NO_2, and SO_2 over 9 cities during 1996 ~ 2003.

3.2.2 Acid Rain Frequency and pH Value

Figure 3 shows trends in pH values of precipitation and acid rain frequency, which continued to fluctuate during 1996 ~ 2003. The pH value ranges from 5.09 to 5.48 as an average over the 9 cities. Compared to other cities, the precipitation acidities of Nantong and those cities to the south of the Yangtze River are higher. The acid rain frequency is negatively correlated with the pH value of precipitation. Overall, the frequency of acid rain shows fluctuations in these years, from 36.7% in 1996 to 23.6% in 1999 to 36.4% in 2003. It reached its lowest in 1999 and rose again after that, indicating that acid rain is still an important issue in this area. Although the total SO_2 emission control policy has been partly effective in recent years, NO_2 emission was not controlled effectively, leading to fluctuations in the pH value of precipitation and acid rain frequency. Therefore, it is not unusual that high acid rain frequency values and low pH values of precipitation in some cities such as Nantong and Nanjing were observed occasionally.

3.2.3 Chemical Composition of Rainwater

The chemical composition of rainwater was further analyzed, which is presented in Fig. 4. Of all the components in rainwater, SO_4^{2-} and NO_3^- ions are the most important, due to their very high concentrations. The trend in SO_4^{2-} concentration is similar to that of SO_2, except for the year 2003. In 2003, the average SO_4^{2-} concentration of the 9 cities is much higher compared to other years. The reason may be that the influence of emissions from other regions outside the area was strong in that year. To understand such issues, more studies are necessary.

NO_3^- concentration exhibits significant increases as with NO_2. The SO_4^{2-}/ NO_3^- ratio was reduced over this period, which means that NO_3^- ions played an increasingly important role in acidification of rain water while the role of SO_4^{2-} declined. These changes resulted mainly from the controlling SO_2 emission from 1996 and the uncontrolled NO_x emissions in recent years.

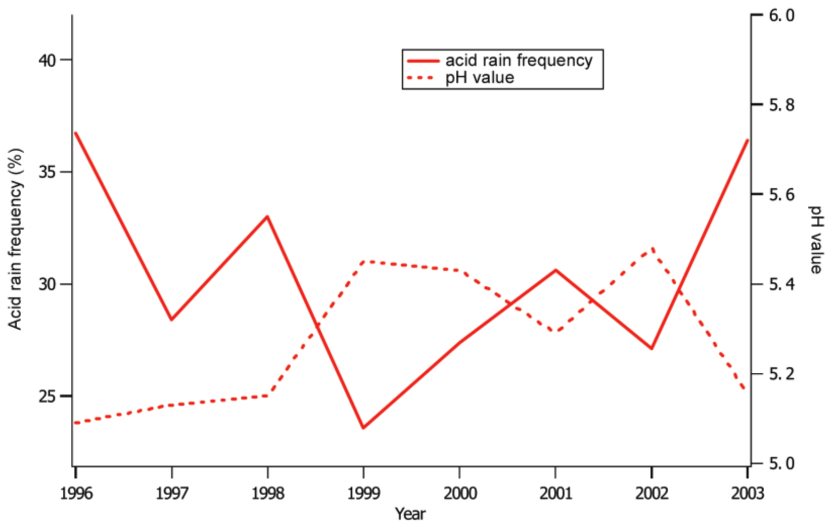

Fig. 3. The trend in pH values and acid rain frequency during 1996 ~ 2003.

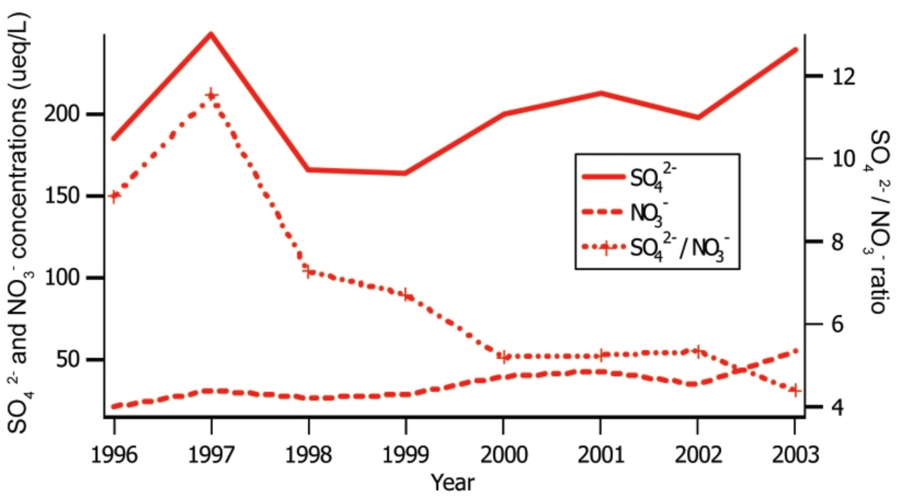

Fig. 4. The trend of SO_4^{2-} and NO_3^- concentrations and SO_4^{2-}/NO_3^- ratio in rainwater during 1996 ~ 2003.

3.3 SO_2 and NO_x Emission

For modeling acid deposition in the YRD region, a comprehensive emission inventory is necessary. Here, SO_2 and NO_x emissions from power plants and other sources was described in Tables 4a and b. The total of the SO_2 and NO_x emissions in each city are obtained from the Environmental Monitoring Stations of Jiangsu Province and Shanghai, while the emissions from power plants are estimated using a routine method based on coal consumption, sulfur content, nitrogen content, burning temperature etc. Total SO_2 emission in the YRD is 1305853 ton, of which 47.6% is from power plants. For Shanghai, Wuxi, Changzhou, Zhenjiang, Nantong, and Yangzhou, the SO_2 emission from power plants in each city accounts for more than 50%

Table 4. (a) SO_2 emission from different sources in the YRD in 2003 (ton yr^{-1}).
(b) NO_x emission from different sources in the YRD in 2003 (ton yr^{-1}).

(a)

City	Power plant emission	Total emission	Power plant/Total（%）
Shanghai	222758	440686	50.5
Nanjing	56963	176461	32.3
Suzhou	91783	277218	33.1
Wuxi	56050	104119	53.8
Changzhou	23926	39896	60.0
Zhenjiang	68834	89324	77.1
Nantong	45456	64405	70.6
Taizhou	9569	23798	40.2
Yangzhou	46203	89946	51.4
Total	621542	1305853	47.6

(b)

City	Power plant emission	Total emission	Power plant/Total（%）
Shanghai	157211	219854	71.5
Nanjing	50273	88444	56.8
Suzhou	65278	83223	78.4
Wuxi	38746	76291	50.8
Changzhou	15803	29628	53.3
Zhenjiang	56804	108433	52.4
Nantong	33895	55893	60.6
Taizhou	4477	6945	64.5
Yangzhou	25400	49513	51.3
Total	447887	718224	62.4

of total SO_2 emission. SO_2 emissions from power plants in Shanghai, Suzhou, and Zhenjiang are larger than other cities. As for total SO_2 emissions, Shanghai, Suzhou, and Nanjing are the top three polluting cities.

Total NO_x emission is 718224 ton, of which 62.4% is from power plants. For Shanghai and Suzhou, NO_x emissions from power plants in each city account for more than 70% of total NO_x emission. The NO_x emissions from power plants in Shanghai, Suzhou, and Zhenjiang are larger than other cities. As for total NO_x emission, Shanghai, Zhenjiang, and Nanjing are the top three polluting cities.

3.4 Simulated Sulfur and Nitrogen Deposition

To understand the spatial distribution of acid deposition in the YRD region, the RegADMS was used to simulate the annual sulfur (S) and nitrogen (N) deposition in 2003. The model was run for 24 periods, with 15 or 16 days in one period. The MM5 was run first to get the meteorological fields, which were used to drive NJURADM. The deposition results are showed in Figs. 5a and b.

Figure 5a shows S deposition due to total sources in the YRD. The spatial distribution of S deposition is relatively homogenous and extensive because of long range transport of SO_2 and its oxidant sulfate (SO_4^{2-}). Most centers with high level S deposition appear in mega cities and power plants, with values over 10 g m^{-2} yr^{-1}. The levels of S deposition in the Shanghai, Suzhou, Nanjing, Zhenjiang, and Yangzhou areas are higher than other cities. For Shanghai and Suzhou, S deposition is over 4 g m^{-2} yr^{-1}. According to a study from RAINS-ASIA (1994), the critical load of S deposition at 50% protective rate (i.e., the percentage whereby the ecosystem cannot be affected due to acid deposition) is 2 - 4 g m^{-2} yr^{-1} over the YRD region. Therefore,

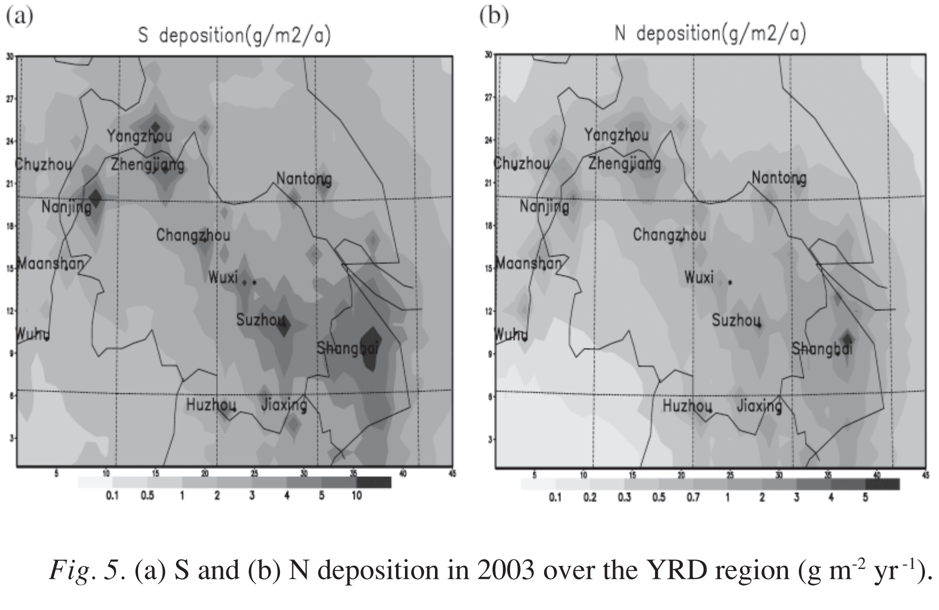

Fig. 5. (a) S and (b) N deposition in 2003 over the YRD region (g m^{-2} yr^{-1}).

it can be concluded that S deposition in the study area is very serious, with expectations that it will have a substantial impact on the ecology of this region.

The statistical results of S deposition are listed in Table 5a. Total S deposition in the YRD is 204752 ton, of which 35.5% comes from power plants. The contribution rate of power plants is between 31.8% and 40.6%, showing little difference in the 9 cities. Since there are many power plants in the study region, SO_2 emissions in one city have a strong influence on S deposition in neighboring cities. In the YRD region, total S deposition accounts for 23.2% of total S emission for power plants. The ratio of total S deposition to total S emission is 31.4%. Other sulfur, accounting for 68.6%, has deposited in neighboring regions or the ocean. For Shanghai and Nanjing, their S emissions are mostly deposited in other cities, with the ratio of S deposition to S emission being 20.7% and 25.9%, respectively. For Nantong and Taizhou, the S deposition to S emission ratio has exceeded 70%, suggesting that S deposition in these cities is possibly transported from neighboring cities.

Figure 5b is N deposition resulting from total NO_x emissions in the YRD. The spatial distribution of N deposition is similar to that of S deposition with much low levels ranging from 0.5 to 3 g m^{-2} yr^{-1}. N deposition in Shanghai is the highest, over 5 g m^{-2} yr^{-1}; this level exceeds the critical load. As reported by Hao et al. (2001), the critical load for N deposition in the YRD is about 4 g m^{-2} yr^{-1}. Thus N deposition in this region is becoming more important to total acid deposition than is S deposition.

Table 5b gives the summary of N deposition. Modeling results show that total N deposition in the YRD is 46835 ton, of which 59.5% comes from power plants. The contribution rate of power plants for N deposition is higher than that for S deposition (35.5%), suggesting that power plants play a more important role in N deposition over the YRD region.

3.5 Cross-Border Transport

Since acid rain is an air pollution problem on a regional scale, acid deposition in certain areas can be contributed to by both local and transported emissions. To understand transboundary transport of air pollutants and their deposition in the YRD region, two numerical experiments were performed. In the first experiment, only emissions of SO_2 and NO_x in Shanghai were considered. Thus, the influence of emissions in Shanghai on sulfur and nitrogen deposition for all 9 cities was estimated. In the second experiment, only emissions of SO_2 and NO_x in the 8 cities of Jiangsu province were considered. Then, sulfur and nitrogen depositions in the 9 cities were investigated. The statistical results are listed in Tables 6a and b.

From Table 6a, the total S deposition in the 8 cities along the Yangtze River contributed to by Shanghai SO_2 emission is 25052 ton yr^{-1}, which is obtained from Table 6a by subtracting the total S deposition in the YRD areas (58182 ton yr^{-1}) by the deposition in Shanghai (33130 ton yr^{-1}). The contribution rate of Shanghai SO_2 emission to S deposition in Suzhou and Nantong accounts for 25.9% and 28.9%, respectively, while it is about 5% for Nanjing, Zhenjiang, and Yangzhou. On the other hand, S deposition in Shanghai resulting from SO_2 emissions in the 8 cities is 12573 ton yr^{-1}, about 27.5% of its total S deposition.

From Table 6b, total N deposition in the 8 cities along the Yangtze River contributed to by Shanghai NO_x emission is 5581 ton yr^{-1}, which is obtained from Table 6b by subtracting the

Table 5. (a) Simulated regional S deposition in different cities over the YRD in 2003 (ton yr^{-1}). (b) Simulated regional N deposition in different cities over the YRD in 2003 (ton yr^{-1}).

(a)

City	Power plant S deposition	Total S deposition	Power plant S deposition/ Total S deposition (%)	Power plant S deposition/ Power plant S emission (%)	Total S deposition/ Total S emission/ (%)
Shanghai	15271	45702	33.4	13.7	20.7
Nanjing	7271	22858	31.8	25.5	25.9
Suzhou	13064	38079	34.3	27.8	27.5
Wuxi	8315	22853	36.4	29.7	43.9
Changzhou	4626	12968	35.7	35.6	65.0
Zhenjiang	5940	14643	40.6	17.2	32.8
Nantong	9884	25615	38.6	43.5	79.5
Taizhou	3898	10085	38.7	81.5	84.8
Yangzhou	4339	11950	36.3	18.8	26.6
Total	72608	204752	35.5	23.2	31.4

(b)

City	Power plant N deposition	Total N deposition	Power plant N deposition/ Total N deposition (%)	Power plant N deposition/ Power plant N emission (%)	Total N deposition/ Total N emission/ (%)
Shanghai	6117	12095	50.6	12.8	18.1
Nanjing	2761	4714	58.6	18.0	17.5
Suzhou	4980	8739	57.0	25.0	34.5
Wuxi	2996	4795	62.5	25.4	20.6
Changzhou	1761	2534	69.5	28.7	28.1
Zhenjiang	2582	3572	72.3	14.8	10.8
Nantong	3510	5688	61.7	29.9	33.4
Taizhou	1413	2161	65.4	103.7	102.2
Yangzhou	1742	2537	68.7	15.4	16.8
Total	27863	46835	59.5	20.2	21.4

Table 6. (a) Simulated S deposition in different areas caused by different sources in year 2003 (ton yr $^{-1}$). (b) Simulated N deposition in different areas caused by different sources in year 2003 (ton yr $^{-1}$).

(a)

Cities	Shanghai emissions	8 cities emissions	YRD emissions	Shanghai emission/ YRD emission (%)	8 cities emissions /YRD emission (%)
Shanghai	33130	12573	45702	72.5	27.5
Nanjing	1192	21666	22858	5.2	94.8
Suzhou	9855	28224	38079	25.9	74.1
Wuxi	2884	19969	22853	12.6	87.4
Changzhou	1116	11852	12968	8.6	91.4
Zhenjiang	747	13896	14643	5.1	94.9
Nantong	7397	18218	25615	28.9	71.1
Taizhou	1168	8917	10085	11.6	88.4
Yangzhou	694	11256	11950	5.8	94.2
Total	58182	146570	204752	28.4	71.6

(b)

Cities	Shanghai emissions	8 cities emissions	YRD emissions	Shanghai emission/ YRD emission (%)	8 cities emissions /YRD emission (%)
Shanghai	9651	2444	12095	79.8	20.2
Nanjing	159	4555	4714	3.4	96.6
Suzhou	2513	6226	8739	28.8	71.2
Wuxi	568	4226	4795	11.9	88.1
Changzhou	202	2332	2534	8	92
Zhenjiang	132	3439	3572	3.7	96.3
Nantong	1676	4013	5688	29.5	70.5
Taizhou	221	1939	2161	10.2	89.8
Yangzhou	109	2428	2537	4.3	95.7
Total	15232	31603	46835	32.5	67.5

total N deposition in YRD areas (15232 ton yr^{-1}) by the deposition in Shanghai (9651 ton yr^{-1}). The contribution rate of Shanghai NO_x emission to N deposition in Suzhou and Nantong account for over 28.8% and 29.5% respectively, while it is about 3% ~ 4% for Nanjing, Zhenjiang and Yangzhou. On the other hand, N deposition in Shanghai resulting from NO_x emissions of the 8 cities is 2444 ton yr^{-1}, about 20.2% of its total N deposition.

The numerical studies above show that cross-border transport of air pollutants between Shanghai and the 8 cities of Jiangsu Province is evident. This is due to meteorological conditions and emission patterns in the study region. Therefore, S and N deposition in one area are attributed to by both local and transported emissions. The contribution rate of each kind of source is important for controlling acid deposition.

4. CONCLUSIONS

As a result of pollution control in Shanghai and the 8 cities of Jiangsu Province, air quality in the Yangtze River Delta region improved from 1996 - 2003. The annual average concentrations of SO_2, NO_2, PM_{10} were 12 ~ 64, 13 ~ 57, 79 ~ 184 $\mu g\ m^{-3}$, respectively. Surface concentrations of PM_{10} declined steadily, decreasing by 39% from 1996 to 2003. However, acid rain is still an important atmospheric environmental issue. The SO_2 concentration decreased before 1999, rose again and then had started to decline again by 2003. Acid rain frequency decreased and the pH value of precipitation increased with fluctuations. For now, the regions with relatively severe acid rain are in Nantong and Changzhou. In addition, emissions of NO_2 have not been well controlled in recent years due to the increasing number of automobiles in city clusters, leading to growth in NO_2 level in the YRD region. Since NO_2 is a precursor of photochemical smog, its effect on secondary air pollution should be addressed as early as possible.

Modeling results show that total annual S and N deposition are 204752 and 46835 ton yr^{-1} in the study region, which account for 31.4% of S emissions and 21.4% of N emissions. Power plants contribute 35.5% of S deposition and 59.5% of N deposition. Cross-border transport of sulfur deposition and nitrogen deposition due to SO_2 and NO_x emissions between Shanghai and the 8 cities of the Yangtze River Delta are significant. The emission from Shanghai contributes 5% ~ 29% of sulfur deposition and 3% ~ 30% of nitrogen deposition in these 8 cities, while the 8 cities contribute 27.5% of sulfur deposition and 20.2% of nitrogen deposition in Shanghai.

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