TRENDS IN EMISSIONS OF ACIDIFYING SPECIES IN ASIA, 1985-1997

DAVID G. STREETS*[1], NANCY Y. TSAI[1], HAJIME AKIMOTO[2], and KAORU OKA[3]

[1] *Decision and Information Sciences Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439, U.S.A.;* [2] *Research Center for Advanced Science and Technology, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153, Japan;* [3] *EX Corporation, 17-22 Takada, Toshima-ku, Tokyo 171, Japan*

(author for correspondence, e-mail: dstreets@anl.gov)*

(Received xxxx 2000; accepted xxxx 2000)

Abstract. Acid deposition is a serious problem throughout much of Asia. Emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) have been increasing steadily, as nations strive to increase their levels of economic development. Coal and fuel oil have been the main choices for powering industrial development; and, until recently, only a few countries (notably Japan and Taiwan) had taken significant steps to avert the atmospheric emissions that accompany fuel combustion. This paper discusses trends in emissions of SO_2 and NO_x that have occurred in Asian countries in the period 1985-1997, using results from the RAINS-ASIA computer model and energy-use trends from the IEA Energy Statistics and Balances database. Emissions of SO_2 in Asia grew from 26.6 Tg in 1985 to 33.7 Tg in 1990 and to 39.2 Tg in 1997. Though SO_2 emissions used to grow as fast as fossil-fuel use, recent limitations on the sulfur content of coal and oil have slowed the growth. The annual-average emissions growth between 1990 and 1997 was only 1.1%, considerably less than the economic growth rate. Emissions of NO_x, on the other hand, continue to grow rapidly, from 14.1 Tg in 1985 to 18.7 Tg in 1990 and 28.5 Tg in 1997, with no signs of abating. Thus, though SO_2 remains the major contributor to acidifying emissions in Asia, the role of NO_x will become more and more important in the future.

Keywords: emissions, acidification, Asia, sulfur dioxide, nitrogen oxides

1. Introduction

Acid deposition is a serious problem throughout much of Asia. The primary causes are emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) to the atmosphere from the combustion of fossil fuels. Emissions of SO_2 and NO_x in Asia are of concern because they are large and growing and because—unlike in Europe and North America—there are few regulations in place to limit their release. Though emissions of both species in Asia are large today, the concern is that they will be much larger in the future—larger than in Europe and North America combined (Streets *et al.*, 1999). Results from the RAINS-ASIA model (Downing *et al.*, 1997) have suggested that under conditions of continued economic development and industrial growth, with no change in environmental policies beyond those that existed in 1990, annual emissions of SO_2 in Asia will

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

increase from 34 Tg in 1990 to 110 Tg by the year 2020 (Foell *et al.*, 1995). Even with a strong emphasis on energy efficiency improvements and a shift away from fossil fuels, 2020 SO_2 emissions in Asia would still be about 80 Tg without abatement measures. The prognosis is even bleaker for NO_x emissions, with projections of an increase from 19 Tg in 1990 to 86 Tg by the year 2020 (van Aardenne *et al.*, 1999).

In a recent paper (Streets *et al.*, 2000), we presented a new method to investigate trends in SO_2 emissions in Asia from 1985-1997. The emission trends are obtained by extrapolating emissions from the detailed, base-year, RAINS-ASIA inventory for 1990 (Arndt *et al.*, 1997; Shrestha *et al.*, 1996), using energy and fuel-use trends from the IEA Energy Statistics and Balances data base (IEA, 1997 and 1999), coupled with information on sulfur control measures that have been introduced since 1990 in the countries of Asia. Changes were determined in the two major parameters driving emission estimates: amounts of fossil fuels and biofuels used, and the degree of emission control (either in the form of reduced sulfur content of fuels or post-combustion abatement through flue-gas desulfurization). Emissions are determined for each sector/fuel combination, for each country, using the following equation:

$$E_{i,t} = E_{i,1990} [P_{i,t} / P_{i,1990}]$$

where: $E_{i,1990}$ is the fuel/sector emissions value from the RAINS-ASIA base-year inventory, and
P is an appropriate parameter from the IEA data series.

It is known that several countries in Asia took steps in the period 1990-1997 to reduce the sulfur content of fuels, particularly oil products. These were usually implemented by regulation. In addition, China's use of high-sulfur coal was reduced during this period. A survey was therefore conducted of changes in sulfur contents of fuels and the year in which the change took effect. These were then implemented within the framework of the RAINS-ASIA model to yield adjusted emission estimates. These adjustments significantly reduced SO_2 emissions for China, Japan, the Republic of Korea, Taiwan and Thailand.

2. Results

Results of the emission trend calculations are summarized in Figure 1 for China alone and for all of Asia. This figure shows trends from the RAINS-ASIA model interpolated between 1990 and 2000 (dashed line), the emission trends developed in this work (open circles), and other estimates of Asian SO_2 emissions (various symbols). The trends obtained by interpolation of the RAINS-ASIA values for 1990 and 2000 show Asian emissions growing from 33.7 Tg in 1990 to 46.4 Tg in 1997, an annual-average growth rate of 4.7%.

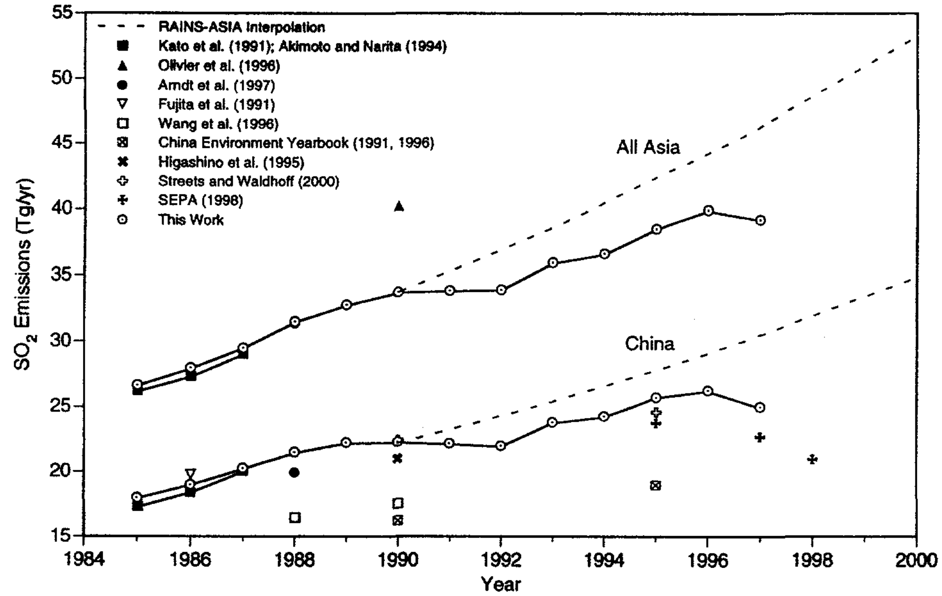

Figure 1. Trends in SO_2 emissions in Asia, 1985-1997.

When sulfur-in-fuel restrictions are taken into account, recent emission trends are significantly lowered. Emissions are now estimated to have grown from 33.7 Tg in 1990 to 39.2 Tg in 1997, an annual-average growth rate of only 2.2%. Much of the reduction is due to trends in China in recent years. Chinese emissions grew slower than expected, and emissions in 1997 were actually less by some 1.2 Tg than in 1996. This can be ascribed to the combination of a slow-down in the Chinese economy, improved efficiency of energy use, a marked reduction in industrial coal use, and a rising awareness of the dangers of air pollution—as manifested in the mining of higher-quality coals and the closing of some high-sulfur coal mines. This trend is consistent with the most recent estimates made by SEPA (1998), which show a decline in emissions between 1995 and 1998 (see Figure 1). Whether this arrest of the increase in China's SO_2 emissions will persist beyond 1998 will depend on the outcome of competition between renewed economic growth, rationalization of China's coal-use policy, and implementation of the "Two-Control-Zone" acid-rain policy. Recently, new finds of natural gas in China have led to substitution of gas for oil and coal in domestic, industrial, and power applications, which will also contribute to a lowering of SO_2 emissions in the future. Figure 1 shows clearly that SO_2 emissions in Asia are no longer inextricably linked to energy consumption (the RAINS-ASIA pathway), which is a positive development for acid deposition in the future.

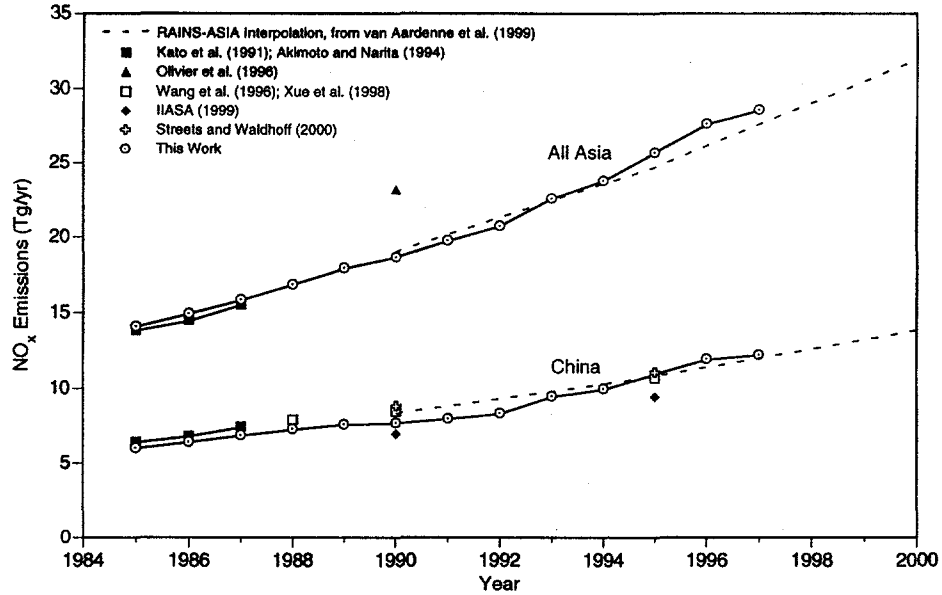

Figure 2. Trends in NO_x emissions in Asia, 1985-1997.

We have now extended the methodology to estimate NO_x emissions, using the same technique to extrapolate emissions by sector and fuel type from the RAINS-ASIA base year of 1990 to other years, using IEA energy data. In this case, we developed our own matrices of emission factors by fuel type and sector. Following the approach of Olivier *et al.* (1996), we developed different sets of emission factors for four regions: the Indian sub-continent, East Asia, the China region, and Japan. The emission factors themselves were selected judiciously from several sources (Olivier *et al.*, 1996; IIASA, 1999; and van Aardenne *et al.*, 1999) to best reflect the range of technologies in place in the region. These emission rates were reflective of NO_x emission controls already in place on large stationary sources in Japan and the lower NO_x emission rates from vehicles in the developed countries of Asia. Figure 2 shows that NO_x emissions in Asia continue to rise in step with energy growth, though a slight deceleration appears to have taken place between 1996 and 1997 due to the reduction in coal use in China. Overall, we find that NO_x emissions grew from 18.7 Tg in 1990 to 28.5 Tg in 1997, an annual-average growth rate of 6.2%. The increase in coal and oil use for power and industrial development is compounded by rapid growth in vehicular transport systems to yield a growth in NO_x that is larger than would be expected in SO_2 emissions, even if sulfur-in-fuel controls had not been instituted. Penetration of NO_x abatement systems outside of Japan has been almost non-existent.

TABLE I

Estimates of national SO_2 and NO_x emissions (Gg/yr) for 1990, 1995, and 1997

	SO_2			NO_x		
Country	**1990**	**1995**	**1997**	**1990**	**1995**	**1997**
Bangladesh	99.7	139.4	144.7	102.7	139.8	144.7
Bhutan	1.4	1.6	1.7	2.0	2.4	2.6
Brunei	6.1	9.1	8.8	16.5	23.7	23.6
Cambodia	23.0	25.7	26.0	31.8	35.8	36.2
P.R. China	22225.3	25697.7	24970.5	7633.3	10919.9	12230.2
Hong Kong, China	152.4	154.6	140.0	216.8	272.1	307.0
India	4437.2	5609.5	6276.6	3235.5	4500.4	4924.4
Indonesia	561.8	683.5	990.5	794.0	1117.7	1310.0
Japan	833.1	782.9	749.8	2817.6	3202.0	3270.2
Korea, D.P.R. of	353.3	256.8	251.5	502.7	349.4	335.5
Korea, Rep. of	1706.4	1219.0	1280.3	929.9	1631.3	1820.7
Lao P.D.R.	3.4	4.6	5.6	4.2	6.4	8.2
Malaysia	255.8	266.8	312.3	310.2	450.1	544.6
Mongolia	80.9	74.6	82.1	38.9	33.6	36.8
Myanmar	19.2	20.8	21.3	45.6	55.4	71.3
Nepal	16.8	35.8	33.2	25.9	37.5	37.4
Pakistan	684.9	908.2	1011.4	344.2	466.0	501.3
Philippines	411.8	475.6	660.2	228.9	298.6	268.9
Singapore	190.8	230.3	208.4	112.6	144.5	138.6
Sri Lanka	26.0	38.0	61.4	47.2	64.3	69.5
Taiwan	504.6	454.1	348.1	530.8	780.7	882.7
Thailand	964.2	1249.4	1322.4	545.7	909.5	1020.0
Vietnam	113.0	133.0	273.0	133.7	187.0	517.1
Total Asia	33670.9	38471.0	39179.5	18650.4	25627.8	28501.4

Table I summarizes national-level emissions for Asian countries for 1990, 1995, and 1997. It is apparent that the restraint on emissions growth has been particularly strong in East Asia (especially China), though this region still contributes the majority of total Asian emissions. Growth in emissions in Southeast Asia has been rapid, despite some restraints imposed in Thailand. Of particular concern are the large increases in the use of heavy fuel oil and coal in such countries as Indonesia, Vietnam, and the Philippines in the period 1995-1997, according to IEA energy statistics. The effects of the economic recession in Southeast Asia in 1997-1998 should become apparent in future inventory updates. In the Indian subcontinent it appears that there have been very few attempts to limit releases to the atmosphere—possibly because of the absence of a clear acid-rain problem—resulting in a steady increase in emissions.

3. Conclusions

It is apparent from this work that SO_2 emissions in Asia are not growing as fast as was thought likely in the early 1990s. Emissions in 1997 (39.2 Tg) are some 7.2 Tg, or 16%, less than was anticipated in the early to mid-1990s (46.4 Tg). This has major implications for SO_2 emissions beyond the year 2000 (see Grubler, 1998). The implementation of China's "Two-Control-Zone" policy, the de-emphasis of coal use, and the spread of environmental awareness from East Asia to Southeast Asia and ultimately the Indian subcontinent all suggest that the vision of rapid and sustained growth of SO_2 emissions in Asia is a thing of the past. Projections of a doubling or tripling of Asia's SO_2 emissions by the year 2020 must now be regarded as outdated. Examination of Figure 1 with an eye to the future suggests that annual Asian SO_2 emissions could well peak at something in the region of 40-45 Tg by the year 2020 or before, in contrast to some of the more dire predictions (80-110 Tg) mentioned earlier. On the other hand, NO_x emissions continue to grow in step with fossil-fuel use, and unless measures are introduced to improve the efficiency of fuel combustion or introduce NO_x abatement measures for stationary sources and vehicles, the outlook is not encouraging for acid deposition in Asia.

Acknowledgements

This work was supported by the World Bank, as part of the RAINS-ASIA project, and by the National Aeronautics and Space Administration, as part of the China-MAP program, under Interagency Agreement S-92591-F with the U.S. Department of Energy. The opinions expressed herein are those of the authors alone and should not be construed as representing the official positions of the World Bank, the U.S. Department of Energy, the National Aeronautics and Space Administration, or the organizations with which the authors are affiliated.

References

Akimoto, H., Narita, H.: 1994, *Atmospheric Environment* **28**, 213.

Arndt, R.L., Carmichael, G.R., Streets, D.G., Bhatti, N.: 1997, *Atmospheric Environment* **31**, 1553.

China Environment Yearbook: 1991, 1996.

Downing, R.J., Ramankutty, R., Shah, J.J.: 1997, *RAINS-ASIA: An Assessment Model for Acid Deposition in Asia*. The World Bank, Washington, D.C.

Foell, W., Green, C., Amann, M., Bhattacharya, S., Carmichael, G., Chadwick, M., Cinderby, S., Haugland, T., Hettelingh, J.-P., Hordijk, L., Kuylenstierna, J., Shah, J., Shrestha, R., Streets, D., Zhao, D.: 1995, *Water, Air, and Soil Pollution* **85**, 2277.

Fujita, S., Ichikawa, Y., Kawaratani, R.K., Tonooka, Y.: 1991, *Atmospheric Environment* **25**, 1409.

Grubler, A.: 1998, *Mitigation and Adaptation Strategies for Global Change* **3**, 383.

Higashino, H., Tonooka, Y., Yanagisawa, Y., Ikeda, Y.: 1995, *Journal of Japanese Society for Atmospheric Environment* **30**, 374 (in Japanese).

IEA: 1997, *Energy Balances of Non-OECD Countries 1960-1995*, software version 4.1; *Energy Statistics of Non-OECD Countries 1960-1995*, software version 4.1; *Energy Statistics of OECD Countries 1960-1995*, software version 4.1. Organisation for Economic Co-operation and Development and the International Energy Agency, Paris.

IEA: 1999, *Energy Statistics of Non-OECD Countries 1996-1997* (September 1999); *Energy Balances of Non-OECD Countries 1996-1997* (September 1999); *Energy Statistics of OECD Countries 1996-1997* (June 1999); *Energy Balances of OECD Countries 1996-1997* (June 1999). Organisation for Economic Co-operation and Development and the International Energy Agency, Paris.

IIASA: 1999, *A Comprehensive Assessment of Large-Scale Environmental Problems in East-Asia*, Final Report to the Central Research Institute of Electric Power Industry (CRIEPI), International Institute for Applied Systems Analysis, Laxenburg, Austria.

Kato, N., Ogawa, Y., Koike, T., Sakamoto, T., Sakamoto, S.: 1991, *Analysis of the structure of energy consumption and the dynamics of emissions of atmospheric species related to the global environmental change (SO_x, NO_x & CO_2) in Asia*. NISTEP Report No. 21, National Institute of Science and Technology Policy, Japan.

Olivier, J.G.J., Bouwman, A.F., van der Maas, C.W.M., Berdowski, J.J.M., Veldt, C., Bloos, J.P.J., Visschedijk, A.J.H., Zandveld, P.Y.J., Haverlag, J.L.: 1996, *Description of EDGAR Version 2.0*. RIVM Report No. 771060 002, Bilthoven, The Netherlands.

SEPA: 1998, *1998 Report on the State of the Environment in China*. State Environmental Protection Administration, Beijing, China.

Shrestha, R.M., Bhattacharya, S.C., Malla, S.: 1996, *Journal of Environmental Management* **46**, 359.

Streets, D.G., Carmichael, G.R., Amann, M., Arndt, R.L.: 1999, *Ambio* **28**, 135.

Streets, D.G., Tsai, N.Y., Akimoto, H., Oka, K.: 2000, *Atmospheric Environment*, in press.

Streets, D.G., Waldhoff, S.T.: 2000, *Atmospheric Environment* **34**, 363.

Van Aardenne, J.A., Carmichael, G.R., Levy, H., Streets, D., Hordijk, L.: 1999, *Atmospheric Environment* 33, 633.

Wang, W., Wang, W., Zhang, W., Hong, S.: 1996, *China Environmental Science* **16**, 161 (in Chinese).

Xue, Z., Yang, Z., Zhao, X., Chai, F., Wang, W.: 1998, *Distribution of SO_2 and NO_x emissions in China, 1995*. Proceedings of the 6th International Conference on Atmospheric Sciences and Applications to Air Quality. Beijing, China.