Baseline Assessment of Acid Deposition in Northeast Asia – Full Text

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Baseline Assessment of Acid Deposition in Northeast Asia

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Introduction

Asia is experiencing rapid economic and population growth. It is estimated that by the year 2010 over 4 billion people will be living in eastern Asia and the Indian sub-continent. Additionally, these countries are experiencing phenomenal economic expansion. For example, China has experienced 9.5% growth in its GDP between 1980 and 1990 (Hoffman, 1994). This rapid growth in the many Asia economies has resulted in significant growth in the region's energy needs (Akimoto and Narita, 1994, and Siddiqi, 1996). Coal is becoming the primary choice for energy production within this region. In 1987, coal accounted for 76 and 35% of the primary energy consumption in China and South Korea, respectively, (Shrestha and Bhattacharya, 1991).

This growth has not come without environmental consequences. Asia is experiencing a rapid increase in air pollutant emissions (Rodhe et al., 1992 and Kato et al., 1991), with growth in sulfur oxide emissions paralleling the region's expanding energy needs (Foell et al., 1995 and Qi et al., 1995). Over the past two decades China's SO2 emissions have grown by more than a factor of three (Cofala, 1995) and this trend is expected to continue. Asia's total SO2 emissions may increase by another factor of three between 1990 and the year 2020 (Foell et al., 1995).

The impact of Asia's deteriorating air quality could have wide-ranging consequences for the region. Many urban centers in Northeast Asia have air pollution levels exceeding WHO ambient standards (Mage et al., 1996 and Florig, 1995). Acidic precipitation is being reported throughout the region (Khemani et al., 1989, Mohammed and Kamsah, 1993, Wang and Wang, 1995), with many areas already receiving levels which exceed the acidic carry capacity of their soils (Hettelingh et al., 1995). According to a recent study conducted by the Chinese Research Academy of Environmental Sciences, 40% of China is affected by acid rain causing US$1.6 billion worth of damage to crops, forests and property annually (Walsh, 1995). The transport and fate of sulfur in Asia is an area of increasing environmental interest and concern (Carmichael and Arndt, 1995, Robertson et al., 1996, Arndt et al., 1996, Sato et al., 1996, and Sharma et al., 1995) as countries receive growing amounts of sulfur from neighboring and even distant countries (Ichikawa and Fujita, 1995, and Arndt et al., 1996b).

In this paper we assess the vulnerability of Northeast Asia to the problems of long range transport of pollutants and acidic deposition. This will be accomplished by looking at the present situation and then exploring the future situation that may result from the growth in energy use as discussed in Streets (1996b). The following discussion is organized in terms of overriding questions regarding acid deposition in Northeast Asia.

Where Do Acidic Species Come From?

In discussing acidic deposition it is important for us to realize that the relationships between the emissions of pollutants and the resultant acid deposition are difficult to determine because of the number and nature of the processes that occur. Acidic deposition arises as a result of several chemical and physical processes which convert primary pollutants such as sulfur dioxides and nitrogen oxides into more strongly acidic (secondary) pollutants. Sulfur and nitrogen containing species along with reactive hydrocarbons are emitted from a variety of anthropogenic and natural sources. These compounds are mixed, transported, reacted, and finally removed from the air back to the earth's surface. Sulfur dioxide is converted by chemical reactions in the atmosphere in the presence of sunlight and water vapor into sulfuric acid, or, depending on the meteorological conditions and the local availability of oxidizing substances, the sulfur dioxide (SO2) may be transported hundreds of kilometers before it reacts. Some SO2 may also be deposited in gaseous form directly to the earth's surface. Some SO2 may be absorbed into cloud droplets, where it may undergo chemical reactions which produce sulfuric acid. This acid may be removed from the atmosphere through the formation of precipitation, or it may be injected into the gas phase through evaporation processes.

In a somewhat similar manner, nitrogen oxides (NO and NO2, referred to together as NO_x) can be transported, dry deposited, or reacted to form nitric acid. Gaseous nitric acid is usually absorbed immediately into available cloud water and is eventually returned to the earth as nitrate ion in precipitation. Organic acids, may also be formed from emitted reactive hydrocarbons, and end up in precipitation. These acidic species cause an acidification of the precipitation (rainwater is classified acidic if the pH is less than 5.6), which in turn can result in adverse environmental impacts. However, pH by itself only tells part of the story. It is not the pH of the rainwater that causes the environmental problems, but rather the response of plants and soils to the chemical constituents of the rainwater. Of most concern is the presence of strong acids such as sulfuric and nitric acids. Thus to assess acidic deposition in Asia we must look at the chemical composition of the precipitation.

Does Acid Deposition Occur in Northeast Asia?

Acid deposition monitoring in Northeast Asia began in the early 1980's. The history of acid rain monitoring in Japan and a summary of the results are nicely presented in papers by Hara (1993) and Murano et al., (1993). The first long term measurements of precipitation chemistry in Japan were undertaken by the Japan Meteorological Agency, as part of the World Meteorological Organization, global precipitation network. They have been monitoring precipitation chemistry at Ryouri (located in northern Japan facing the Pacific Ocean) since 1976. In 1983 the Japan Environmental Agency (JEA) organized the Committee of Acid Deposition to launch a 5-year project on acid deposition monitoring, which has continued to the present day. The measurements at Ryouri show that the pH levels were 5.2 in the late 1970's and now are below 4.7 (pH is a logarithmic scale so this indicates an increase in acidity of ~ 5 times). The acidity is due predominately to sulfate and nitrate, with sulfate contributing 3 times more acidity than nitrate. The amount of sulfate deposited at this site has remained fairly constant, but the nitrate levels have continued to increase. This location tends to be most heavily influenced by Japanese emissions, and thus the deposition follows the general trends in Japanese emissions discussed in Streets (1996b), where SO2 has decreased while NOx emissions have increased during this time period.

Examination of the JEA network, which provides information from 29 sites throughout Japan, shows that the pH values (annual values) range from 4.3 to 5.3, with sulfate again being the major acid followed by nitrate. (A map summarizing the pH values in Japan is shown in Figure 1.) Thus, the precipitation throughout Japan is classified as acidic. However, no discernible trend in pH with respect to time is apparent from these data. These values can be compared to those measured in Europe and North America (also shown in Figure 1) where the values range from 4.4 to 6.5 and 4.2 to 5.6, respectively. The pH levels in Japan are similar to those measured in areas in Europe and North America where acid deposition problems have occurred.

In Japan there have been impacts which are being associated with acid deposition. Sekiguichi (1987) reported dieback of Japanese Cedar in a wide region covering the western and northwestern areas of the Kanto plain. The cause has been discussed in terms of acidification of the soils, as well as magnesium deficiency, exposure to atmospheric ozone, excess supply of nitrogen compounds, and water deficiencies.

A distinctive fact which is often missed when looking at precipitation chemistry in Asia is the role of bases. For example, Northeast Asia is characterized by high levels of ammonium and calcium. These constituents arise from agricultural activities (e.g., livestock and human wastes, and fertilizers in the case of ammonia) and from windblown dust (kosa, yellow sand in the case of calcium) and are basic, meaning that they can neutralize the strong acids. Although the levels of the strong acids (e.g., sulfate and nitrate) in precipitation are frequently equal to or greater than those measured in other areas the pH values remain high due to the presence of these bases. In the case of Japan, their monitoring data suggests that ~50% of the strong acids are neutralized by these basic compounds.

China began a comprehensive survey of acid deposition in 1982, under the auspices of the Chinese National Environmental Protection Agency. These data have been analyzed by Wang and Wang (1995). The pH values of rainwater vary remarkably throughout China (see Figure 2). In the western half of China the pH values range from 6 to 7, indicating that the rain is not acidic but actually is basic! In the southeastern regions, the pH levels are strongly acidic, with annual mean values falling below 4.0. The northeast regions of China have pH levels which are higher than those in the south, but which are still acidic. The contour of pH levels equal to 5.6 extends just to the west of Beijing and along the eastern edge of the Greater Khingan mountain range. A comparison of the situation in 1982 with that at the present time shows clearly that the extent of the geographical region receiving acidic deposition has expanded greatly during the last decade. The regions receiving acidic deposition in 1982 were restricted to the southeast regions well below Beijing. The area receiving acid deposition has increased by 600,000 - 700,000 km2 since 1982 (Wang et al., 1993)!

The contrast between the north and south regions of China is important. Throughout China sulfate dominates the strong acids in the rainwater. The levels of sulfate in the rainwater are similar in both the north and the south. However, the northern regions (approximately that region north of the Yangtze river), are heavily influenced by wind blown soils. Highly basic soils originating from the Taklimakan and Gobi deserts are blown throughout this region and serve to neutralize the strong acids arising from air pollutants in the northern regions. However, as indicated by this data, the strong acids are now often exceeding the capacity of this natural buffer, and the regions of acid deposition are expanding. This situation is important in other regions of Asia as well. A similar situation exists now in India, where large quantities of strong acids are being deposited, but where the pH levels remain relatively high due to alkaline soils associated with their arid regions. However, pH levels are becoming acidic as the levels of strong acids rise with their increased use of fossil fuel.

Acid deposition data throughout Asia has been reviewed by Ayers and Hara (1996). A similar picture as that described above emerges when we look at acid deposition in Korea, Taiwan, Hong Kong and other regions of Asia.

How Much of the Acidic Deposition is Due to Local Emissions?

The observational data shows that acidic deposition occurs throughout Northeast Asia, and that it is due predominately to sulfur species at present, but with a growing contribution due to nitrate. An important question to address is what fraction of the acid deposition at a given location is due to local emissions? versus that due to pollutants which arise from activities located in another county, prefecture or country? A recent analysis of sulfur deposition in Japan conducted by Dr. Fujita (1996) at Central Research Institute for Electric Power Industry (CRIEPI), which utilized present measurements and estimates of sulfur emissions, concludes that Japan receives more sulfur deposition than can be attributed to its own emissions!

Figure 1. Rainwater pH in Japan as measured in the JEA Phase-II Survey. Also shown are pH values in Europe and USA. From Hara (1993). [available in hard-copy version only]

Figure 2. Rainwater pH in China in 1982 and 1992 (from Wang et al., 1995) [available in hard-copy version only]

This suggests that transboundary pollutant transport is already an important occurrence in this region. The possibility of a significant contribution of long range transport of pollutants to acid deposition in the region, should come as no surprise. People in Northeast Asia are well aware of the long range transport of dust. During spring months dust storms (also referred to as yellow sand or kosa) over the central China deserts transport large quantities of dust into the middle troposphere. The resulting dust clouds travel behind cold fronts and can be transported thousands of kilometers away from the source regions (Merrill et al., 1985). During the peak season for dust storms (April, May and June) the region is under the influence of westerly flows so that the dust is transported over Korea and Japan and out into the central Pacific Ocean. It is estimated that the airborne transport and subsequent deposition of dust accounts for 20 to 70% of the total mineral material input into the Yellow Sea. This appreciation of dust transport from China, coupled with China's growing sulfur emissions, has resulted in eyes focused towards China as a logical source of Korea's and Japan's *excess* acid deposition.

Such dust studies, along with the analysis of aerosol and precipitation chemistry measurements, and modeling studies support the idea that transboundary transport is a common occurrence in this region. Transboundary transport in Northeast Asia is no longer in doubt scientifically, and is beginning to be recognized politically.

How and where sulfur (and other pollutants transported long distances) will be deposited is an area of increasing environmental concern (Rodhe et al., 1992 and Hordijk et al., 1995). A number of models have been developed to understand the transport and deposition of sulfur in the region (including among others: Robertson et al., 1995; Sato et al., 1996; Arndt et al., 1995; Kotamarthi and Carmichael, 1990; Ichikawa and Fujita, 1995; Katatani et al., 1992). These models assist investigators in understanding the impact of current emissions on sulfur deposition in Asia and anticipating how projected emissions may affect the region's environment in the future.

To better understand how future emissions may affect acidification in Asia, it is necessary to develop relationships between sources of sulfur and their resulting deposition patterns. As part of the RAINS-ASIA Project (Foell et al., 1995) a long range transport model (ATMOS) was developed for studying the transport and deposition of sulfur in Asia (Arndt et al., 1996, Arndt and Carmichael, 1995). The ATMOS model calculates the deposition from each emission source directly, allowing deposition from a specific point source, region, or country to be analyzed separately.

We have used this model to investigate source-receptor relationships for Asia and have calculated sulfur deposition for the Base Year 1990, using the SO2 emission inventory described in Streets (1996b). The gridded SO2 emissions for 1990 are shown in Figure 3. Shown are the emissions from all anthropogenic sources included in the model (LPS and area sources), shipping and volcanoes. The areas of high population and intense industrial activity are clearly depicted. Northeast Asia represents the region with the highest emissions. The model calculated annual total deposition in grams-sulfur per meter squared per year (g-S/m2-yr)is presented in Figure 4. This map provides an Asia-wide perspective on acid deposition. There are very few regions in Asia which are not impacted by sulfur deposition. The high sulfur deposition regions follow closely the spatial distribution and the density of the emissions. For example, the dense emission regions in eastern and southern China, South Korea, northern Thailand, and eastern India all show elevated sulfur deposition. The highest annual deposition (~10.5 g-S/m2-yr) occurs around the city of Chongqing in Sichuan province. The strong continental outflow of sulfur from East Asia is also clearly depicted. Sulfur emissions in the latitude band 20^{o} to 40^{o} N result in high sulfur deposition virtually throughout the western Pacific Ocean at these latitudes, with Japan and Korea displaying deposition levels ranging from 0.5 to 6 g-S/m2-yr. It is interesting to note that we estimate that ~70% of the emissions in Asia are deposited within the study region, with the remainder being transported out of the region (and into the central Pacific Ocean, and even to North America! This is similar to estimates for the fate of emissions from North American and Western European emissions (Welpdale, 1996).

Figure 3. 1990 annual sulfur emissions AND

Figure 4. Calculated 1990 sulfur deposition [available in hard-copy version only]

What Are the Source-Receptor Relationships in Northeast Asia ?

The ATMOS model calculates the deposition from each source directly and this information can be used to analyze a variety of policy-related questions. For example, the deposition from a specific LPS, region, or country can be viewed separately. This information can also be used to identify which sources contribute to the deposition at a specified receptor, and can be aggregated to provide source-receptor information at a country-to-country or region-to-region level. (Please note that the source-receptor information presented is based on only one year of meteorology and must be considered preliminary.) This information related to source-receptor relationships is of great interest in the region. The interaction between emission sources and their resulting deposition patterns in Northeast Asia is of particular interest since this region has the highest sulfur emissions in Asia (Hara, 1994; Huang et al., 1995; and Murano et al., 1993).

The sources of sulfur deposition at five locations within Japan are presented in Figure 5. Shown are the contributions to the "*controllable*" sulfur (i.e., that due to anthropogenic activity). The variation in Japan's deposition is driven by volcanic, Chinese, South Korean, and Japanese emissions. China's influence is shown to be most evident along the western coast of Honshu and the island of Kyushu, with the smallest impact on Hokkaido in the north. Although Japanese sources are the primary source of anthropogenic deposition throughout Japan, their contribution is highest in eastern Japan, accounting for over 60% of the total deposition. The influence of volcanic emissions on Japan's deposition pattern is also evident, particularly on Hokkaido. Here large emissions from volcanic sources and small influences from anthropogenic sources result in volcanoes accounting for over 60% of the total deposition. Please note that Russian emissions are not included in the analysis. These emissions would have their largest impact on Japan's northern regions, where they are estimated to increase acid deposition by 10 to 20% (Ichikawa and Fujita (1995).

More explicit information is seen by examining the 1990 source-receptor relations for the 23 regions in Northeast Asia as defined in Streets (1996b). This information is presented in Table 1. Each row represents deposition on a specific region (i.e., the *receptor* location), while each column represents the per cent contribution of deposition due to emissions originating from the designated *source* regions. For example, from the row Kyushu-Okinawa we see that 20% of the deposition is due to its own emissions, while 21% comes from emissions in Pusan, South Korea, and an additional 8% comes from emissions in Jiangsu, China. As another example, we see that in Shanghai only 53% of the anthropogenic sulfur deposition comes from its own emissions, with emissions from Jiangsu and Zhejiang Provinces, providing 24% and 18%, respectively. This table clearly identifies that sulfur deposition at a particular receptor can be affected by emissions located hundreds of kilometers away.

Table 2 illustrates the role that China plays in the region in regards to acid deposition. China accounts for ~65% (~22 million tonnes of SO2 per year) of the total emissions in Asia. Of China's emissions, 83% and 14% are deposited on China and the region's oceans, respectively. The remaining 3% falls on other nations (i.e. 0.8% on N. Korea and 0.5% on Japan). Column three presents the fraction of the country's total deposition resulting from China. For example, 98% of the sulfur deposited in China is from Chinese sources while 35% and 39% of the sulfur deposited in North Korea and Vietnam, respectively, is due to Chinese emissions. This table provide an interesting perspective on the region's deposition. Although 97% of China's emissions deposited in the region fall either within China or on the region's oceans, we see that the remaining 3% can account for significant percentages of the neighboring countries' total deposition !

Figure 5. Calculated annual sulfur deposition sources and their fraction contributions for five locations in Japan. [available in hard-copy version only]

Another important point in this regard is that the transport patterns show significant variation throughout the year with continental outflow during the winter and spring and onshore flows during the summer and fall. These flow fields combine with precipitation patterns to significantly alter the source-receptor relationships during the year. Throughout much of Northeast Asia deposition amounts exhibit similar patterns with minimum deposition occurring in the winter and spring and maximum values in the summer.

During the winter and spring months, low precipitation levels over the northern half of China result in the sulfur emitted in this area experiencing very little wet removal. As a result, this sulfur is transported farther from its point of origin then similar emissions released during the summer months when precipitation is higher and the pollutant is more likely to be washed out closer to its point of origin. Hence, SO2 released in northern China during the winter and spring months has a longer "lifetime" then its summer-time counterpart. Additionally, the presence of strong prevailing westerlies during the winter and spring cause the pollutant to be carried farther from its source location. As a result of these greater transport distances a higher fraction of the emitted SO_2 is converted to sulfate. The net effect is that Chinese emissions are more likely to be deposited within China during the summer than during the winter. These factors can be quantified by comparing where Chinese emissions are deposited throughout the year. China's deposition on its own soils is over 50% higher during the summer as compared to winter, despite the fact that due to the domestic heating cycle sulfur emissions in the winter months are 16% higher than during the summer months. Rodhe and Granat (1984) reported a similar phenomenon for European sources.

Table 1. Regional source-receptor relationships for Eastern Asia [available in hard copy only]

Table 2. China's contribution to *controllable* sulfur deposition in the region, expressed both as a percentage of China's total deposition in the region and as a percentage of the receptor- country's total deposition.

Table 2Country-To-Country Source-Receptor

RECEPTOR	% OF CHINA'S DEPOSITION IN ASIA	% OF RECEPTOR'S TOTAL DEPOSITION
China	83	98
Oceans	14	37
North Korea	0.8	35
South Korea	0.4	13
Japan	0.5	17
Vietnam	0.4	39

Winter precipitation along the western coast of Japan is quite high when compared with other northern latitude locations in Northeast Asia. This acts as a strong mechanism for removal of airborne sulfur species. The greater transport of sulfur away from the Chinese mainland during the winter, along with the elevated precipitation levels in western Japan during the winter, results in high deposition of acidic species in Japan during the winter. Furthermore, the contribution of Chinese sources to acid deposition in Japan is 2 to 3 times higher for the winter and spring then for summer and autumn. The same phenomenon is found when comparing winter and summer deposition from South Korea. Deposition on Japan due to South Korean sources is over two times higher during the winter than it is in the summer. In contrast, during the summer, when on-shore winds predominate, sulfur from Japanese sources reaches South Korea. Transport out of the study area is also higher during the winter and spring months.

The important point from the above discussion is that in Northeast Asia, source-receptor relationships can vary by season with a country (or region) changing from being downwind of other countries sulfur emissions, to being the upwind source of acid deposition.

How Much Confidence Do We Have in These Results?

A detailed evaluation of model performance is not pssible due to a lack of a comprehensive observational data set for acid deposition throughout Asia. However, the model has been compared to various data sets in the region. For example, CRIEPI has developed an air quality monitoring network in East Asia with locations in Japan, South Korea, China, and Taiwan (CRIEPI, 1994). This network reflects a widespread variation in geographic locations and emission source magnitudes. The observed annual averaged sulfate concentrations at 16 locations throughout these four countries are presented along with model calculated concentrations in Figure 6. The model captures both the spatial variation and magnitude of the observed values at most locations. The model calculated deposition values have also been compared with JEA monitoring networks in Japan discussed previously (Arndt et al., 1996). Although the model has a tendency to under-predict deposition, especially at those monitoring sites located near major urban areas, the model does accurately capture the spatial variability in the sulfur deposition. Furthermore, Murano (1994) found that wet sulfate deposition accounts for over half of the sulfate deposition on Japan. Of the estimated 1 Tg S deposited on Japan each year Fujita (1996), ~70% is due to wet deposition (Ichikawa and Fujita, 1995). The ATMOS model results are consistent with these estimates, predicting that 60% of the total deposition in Japan is due to wet removal processes.

The model predictions have also been compared with observations from a SO_2 monitoring network in Asia (Carmichael et al., 1995). In addition to capturing annual averages, the model also captures monthly variations in concentrations at these locations. The model provides a reasonable representation of the seasonal variation of monthly concentrations and captures the maximum and minimum seasons at most locations. The model also captures the wide variations in concentration levels between the different sites. For example, while Yangyang, South Korea, experiences monthly average concentrations as high as 10 mg m-3, Mersing, Malaysia, has monthly values less than 1mg m-3, the model results correctly reflect this variation. The influence of precipitation on the concentrations at these locations is also captured. The winter monsoons over Southeast Asia serve to decrease concentrations in Thailand and Malaysia during this time. Similarly, the rainy season in South Korea also results in corresponding low SO_2 concentrations at that time. Due to the coarseness of the model, local influences can be lost in the calculated values.

Figure 6. Comparison of observed (CRIEPI, 1994) and ATMOS predicted annual sulfate concentrations.

These preliminary results, while identifying the need to perform a rigorous model evaluation, provide some confidence that the model can provide a reasonable representation of Asia's deposition pattern.

Some preliminary work on comparing and contrasting acid deposition models applied to Northeast Asia has begun. These have included comparing CRIEPI (Ichikawa and Fujita, 1995) and ATMOS trajectory model results with eulerian results using the STEM model (Carmichael et al., 1991) and the model of Murao (Katatani et al., 1992). These findings have been reported by Phadnis et al., (1996) and Katatani (1996). In general the models are relatively consistent in their prediction of total sulfur deposition.

Although the predictions of total deposition are quite consistent between the various models, there are important differences between the calculated source-receptor relationships. For example, as presented above we estimate that China accounts for ~17% of Japan's *controllable* acid deposition. Source-receptor relationships in East Asia have also been investigated by Huang et al. (1995) and Ichikawa and Fujita (1995). Their calculated contribution of Chinese sources to Japan's deposition present markedly different estimates of the role that long-range transport plays in Japan's over-all deposition. Huang et al. estimate that China accounts for only 3.5% of Japan's total sulfur deposition. They found that over 93% of the sulfur deposited within Japan was from either Japanese anthropogenic or volcanic sources. In contrast, Ichikawa and Fujita (1995) estimate China to be a major source of wet sulfate deposition in Japan, accounting for one-half of the anthropogenic deposition. Our estimate falls between these values. We have begun to study the reasons for the differences between these findings. We have found that the variations in source-receptor relationships are largely due to differences in removal rates and chemical conversion rates assumed in the models. For example, the use of a low removal rate (such as is the case in Ichikawa and Fujita (1995)) results in a greater transport of sulfur away from source locations, and thus a larger contribution to Japan's deposition from emissions in China.

There is clearly a great need to conduct more model comparisons and fundamental studies to better determine the most suitable parameters for use in modeling studies in Northeast Asia. Until such studies are done all source-receptor relationships - including those shown in Table 2 - must be treated with extreme caution. Moreover, these estimates are not yet sufficiently robust to serve as the foundation for policy analysis related to allocation of responsibility and liability for transboundary air pollution in the Northeast Asian region. Conversely, the models already demonstrate clearly the need to address the issue of acid deposition at the source - whatever the ultimate transboundary distribution of the acid rain precursors. Clearly, this is an important area which requires further work. Such studies are planned as part of the RAINS-Asia Phase-II project.

What Are the Environmental Implications of Present Levels of Acid Deposition?

The environmental implications of sulfur deposition cannot be evaluated simply by examining the sulfur deposition amounts at a specific location. Rather, deposition values must be compared with the ability of the receptor locations to assimilate the sulfur deposited. The environmental impacts of sulfur deposition in Asia are being assessed through use of estimates of critical loads (Hettelingh, 1991). A critical load is the maximum level of pollutant that can be deposited on a specific location without environmental damage and provides a means for assessing the environmental risks arising from sulfur deposition. The concept of critical loads is widely accepted in Europe (Hettelingh, 1995) and is beginning to be seriously studied in Asia (Xie et al., 1995). In this study we compare critical loads with the estimates of sulfur deposition to identify which ecosystems may be at risk under various emission scenarios. The areas identified in this way should be viewed simply as regions at *potential* risk, and the prediction of damage based on the concept of critical loads in Asian countries awaits verification.

Presented in Figure 7 are the calculated sulfur exceedances (i.e., the difference between sulfur deposition and the sulfur 20% critical loads levels which represents sulfur deposition amounts that protect 80% of the ecosystems) for 1990. To account for uncertainties in the estimate of critical loads, we chose to use the 20%-levels in our analysis, which are more lenient then the 5%-levels used in Europe All colored areas indicate those regions where sulfur deposition exceeds the critical load, and thus those areas where ecosystems are predicted to be at risk. Vast regions of Asia are predicted to be in excess of the critical load. These areas include vast regions of east and south China, South Korea, southern Japan, Taiwan, and areas in India, Bangladesh, Thailand, Malaysia and

Indonesia.

Figure 7. Calculated sulfur exceedances for 1990. [available in hard-copy version only]

What Are the Possible Environmental Futures for Acid Deposition in Northeast Asia?

The rapid increase in energy consumption in Asia will certainly result in a large growth in sulfur emissions. Without the introduction of additional emissions controls to counter this growth, elevated pollutant levels can be anticipated in this region. To understand the potential future damage (i.e., *risk*) to the region's ecosystems, several energy and emission scenarios were evaluated. Specifically those scenarios outlined in Streets (1996b) were utilized. These consisted of: the "business-as-usual" scenario (BAS); the best available technology (BAT) scenario; the advanced control technology (ACT) scenario; the basic control technology (BCT) scenario; and a high energy efficient scenario (HEF). Each of these were used to project SO2 emission into the year 2020, and the resulting acid deposition was calculated using these new emissions (but with the assumption that the meteorology was not changed as a result of these emissions).

How bleak is the Business as Usual (BAS) future?

The BAS growth is designated as the continued increase in energy consumption without further sulfur emissions controls or modifications to energy production methods (e.g., replacement of coal burning with natural gas usage or reduction of biomass burning). By maintaining current emission practices it is estimated that emissions will reach three times the current levels by the year 2020 except in Japan. Using these emissions, the sulfur deposition and exceedances for the year 2020 were calculated and the 2020 exceedances are shown in Figure 8. Under the assumptions of this BAS scenario, excess deposition would reach unprecedented levels in some regions. We calculate that critical loads would be exceeded by between two and five grams sulfur per square meter per year in large parts of central and eastern China. The highest excess deposition (up to 15 to 20 grams sulfur per square meter per year) is calculated for some ecosystems in Korea, and in the Sichuan and Shanghai provinces. These values are greater than the highest levels ever measured in the Black Triangle region of eastern Europe! In Japan, the region where ecosystems are identified to be at risk to acid deposition extend from Kyushu through central Honshu, and cover more than half of the country.

Although the current state of scientific knowledge does not yet allow drawing conclusions about the environmental damage implied with such excess deposition, the fact that sulfur deposition will be more than ten times above the sustainable levels in large areas may give reason for serious concern. To derive more specific information on potential environmental threats, the RAINS-ASIA model enables the examination of conditions for various types of ecosystems individually. We conclude that the growth of sulfur deposition could have a severe negative influence on the conditions of many important agricultural crops in Asia. The fact that the major rice growing areas in Asia (e.g., in China, and Korea) would experience excess deposition of up to 15 grams per square meter per year is cause for serious concern.

Figure 8. Calculated sulfur exceedances for various emission control scenarios for the year 2020[available in hard-copy version only]

Obviously, acid deposition represents only one potential cause for environmental damage. Our analysis shows that high deposition is always linked to high levels of ambient concentrations. We estimate that in this BAS scenario that the SO2 levels in the rice growing regions in China would reach up to 60 micrograms SO2/m3. Although specific analysis of dose-response relationships for rice paddies is still lacking, a rough extrapolation of the threshold levels (concentrations above which negative impacts are expected) for similar ecosystems (which range usually from 20 to 30 micrograms SO2/m3, see e.g. IUFRO, 1978) suggests that these levels are two to three higher than the threshold values.

High ambient levels of SO2 concentrations resulting from this scenario do not only imply serious risks to natural and agricultural ecosystems, but also impose a serious threat to human health. One of the first and most visible signals is the deterioration of urban air quality in large metropolitan agglomerations in Asia. Our results indicate that this unabated scenario would lead to air pollution levels which exceed the WHO guideline of 40-60 micrograms SO2/m3 (annual average - WHO, 1979) throughout large parts of the region. We have recently explored this aspect in more detail in the Jiangsu and Shanghai areas (Chang et al., 1996). From a human health risk standpoint, we confirmed the fact that large regions are currently being exposed to SO2 concentrations in excess of the WMO long-term exposure guideline, with isolated regions having concentrations in excess of the short-term exposure guidelines. The situation forecasted for 2010 was markedly different with essentially the entire domain exceeding the long-term guidelines and significant regions exposed to concentrations well in excess of the short-term guidelines. Adverse risks to increased levels of ambient sulfate aerosol were also identified as another growing health concern in the region. These results suggest that the public health impacts in China due to the rapid rise in emissions will be large, and in many locations will be more significant that the impacts due to acid deposition. The issues of human health and acidic deposition should be treaty as a common problem since they both are a result of the high and growing emissions of SO_2.

The results from our study also suggest that the continued growth of sulfur emissions may have profound impacts on the agricultural productivity of the region. The lower Yangzte River delta and the northern regions are projected to be at risk to both direct and indirect effects of air pollution and acid deposition. The central regions of Jiangsu, while projected not to be at risk to acid deposition, are identified to be at risk due to high levels of ambient SO2. These preliminary results indicate the nature of the potential impacts and the challenges that this region faces over the next few decades. Although this paper looked solely at the effects of increases in sulfur emissions, the attendant increase in NOx emissions will also pose additional environmental concerns through increases in ambient ozone levels, and acid deposition (via nitric acid).

What differences can sulfur emission controls and energy efficiency make?

As outlined above it can be expected that the growth in SO2 emissions associated with the envisaged evolution of energy use gives reason for serious concern about maintaining sustainable conditions for natural and agricultural ecosystems in Asia. If no countermeasures are taken, our results suggest a degradation of the environmental quality to unprecedented levels. In response to the finding of the previous section we explored the environmental benefits of alternative strategies for reducing SO2 emissions.

The BAT scenario explores ecological improvements offered by advanced technology as a means to reduce emissions. The measures considered in this scenario represent the current technological standards in many industrialized countries. In particular, wet flue gas desulfurization (WFGD) processes are assumed for all industrial and power plant boilers burning coal and oil, including retrofits of the existing boiler stock. In the residential/commercial (domestic) sector and in the transport sector the use of low sulfur fuels (low sulfur coal, low sulfur oil) is assumed for all small sources.

Advanced emission control methods applied to the fuel consumption levels as suggested by the reference energy scenario could drastically reduce SO2 emissions in Asia below the current levels. Between 1990 and 2020, SO2 emissions from Northeast Asia would decline by ~60 percent, despite the assumed growth in energy consumption. Since control technologies work most effectively at large sources, the relative contribution from large point sources declines from 16 percent in 1990 to less than nine percent in 2020. Note, that this is in contrast to the unabated scenario, in which the share of large point sources increases to 25 percent. Not surprisingly, declining emissions would result in substantial reductions in sulfur deposition. Most interesting, however, is a comparison between the diminished deposition and the critical loads. As displayed in Figure 8, a general use of advanced emission control technologies brings down sulfur deposition below the critical loads throughout most of the region. However, even under this scenario exceedances of critical loads remain in southeastern China and Korea, where sensitive ecosystems are located in regions with intense economic activity. Japan's risk to acid deposition is essentially eliminated under this scenario.

The scenario shows that, despite the more than three-fold increase in energy consumption expected for the next few decades, sustainable conditions - at least in terms of sulfur deposition - could be achieved by advanced technologies for most of the Asian ecosystems. As already discussed in Streets (1996b), the success in ecosystem protection achievable with advanced control technologies, however, has its price. In the year 2020 full application of advanced emission control technologies would require US$35 billion per year (1990 dollars), which is about 0.6 percent of the regional GDP assumed for the underlying energy scenario. For comparison, the relative costs for the latest agreement on reducing sulfur emissions in Europe (the Oslo protocol) were only about one third of this level (0.2 percent of the GDP; Amann *et al.*, 1994). It should be pointed out that there exists a wide range in burdens to the various national economies: Whereas for some countries with highly developed economies (e.g., Japan) the abatement costs are comparably low (0.05 and 0.06 percent, respectively), developing countries with a heavy reliance on coal face substantially higher burdens (e.g., China, 1.7 percent). In Europe, the highest share of GDP for the latest agreement was 0.8 percent.

Since the environmental benefits of such a strategy cannot yet be quantified in monetary terms, a definite answer about the cost-benefit ratio of fully applying western emission control standards cannot be derived yet. It has to be observed, however, that the costs associated with such a strategy would put significant burdens on many developing economies in the region. Consequently, below we search for alternative, perhaps more cost-effective, solutions to reduce source emissions in Asia.

An obvious option for cost-savings would be to select only the most cost-effective measures to reduce emissions. If structural changes in the energy system, such as energy conservation measures and fuel substitution, are left aside for a moment, the remaining technologies show a wide range of cost-effectiveness. A rational policy could therefore request only the most cost-effective measures, thereby reducing the achieved emission reductions to some degree, but to a greater extent also the involved costs. To follow this idea further, we constructed a scenario which assumed that only advanced control technologies (wet flue gas desulfurization WFGD) were applied in new, large emission sources in the power plant, the industrial and refinery sectors. In this scenario, emissions from existing power stations and from small sources in the industry are assumed to be controlled through the use of low sulfur fuels (50 percent share of low sulfur coal and oil). Also in the domestic and transport sectors low sulfur fuels are prescribed. For Japan and Taiwan, however, the scenario assumes compliance with current national legislation. This is the 'advanced control technology'

(ACT) scenario.

As expected, restricting advanced measures to certain sources lowers the emission reductions. Whereas the BAT strategy would cut total SO_2 emissions in Northeast Asia by ~60% in 2020, the ACT scenario produces a 40 percent increase of emissions. However, this level is still less than half of the unabated levels. Selecting only the most cost-effective measures cuts down costs, from more than US$ 35 billion/year (costs for the BAT scenario in 2020) to US$ 14 billion/year (costs drop by about 60 percent). Consequently, in terms of GDP this strategy would take 0.25 percent, which is already close to the 0.21 percent level currently discussed in Europe. Due to country-specific structural differences, the actual situation varies considerably among countries. In China, where the BAT strategy would consume 1.7 percent of GDP, limiting measures to the more cost-effective technologies will reduce the share to 0.6 percent of the GDP. (Please note that these estimates assume all the costs are attributed to emission reductions only.) As shown in Figure 8, under this scenario areas with serious excess deposition are restricted to Korea and some Chinese provinces, whereas in most other regions the deposition could be maintained below the critical loads.

Although emission control costs are reduced significantly in the ACT scenario, the construction of such emission control devices according to world standards requires substantial technical know-how and capital investments. Experience shows that developing countries often have limited access to the necessary technical and financial resources needed to implement advanced technological solutions. Consequently, preference is often given to less advanced approaches readily available on the domestic market, which are also often less capital intensive. To explore the economic and ecological features of strategies that give preference to domestic technologies an indicative scenario was constructed, in which use is made of domestically available control technologies. Therefore, instead of installing standard flue gas desulfurization units at large power stations, emissions from these sources would be controlled through more basic technologies with low capital requirements.

The 'basic control technology' (BCT) scenario assumes that in China emissions from new large point sources are controlled by domestic technology (with a typical removal efficiency of about 50 percent) rather than by advanced flue gas cleaning methods (with efficiencies of more than 90 percent). For small sources in the industrial and domestic sector the use of low sulfur fuels is assumed. Under this scenario SO_2 emissions for the Northeast Asia region are increased from the 1990 levels by ~70%, but are 60% of the unabated 2020 emissions. It is interesting to note however that total costs are essentially the same as those for the ACT scenario as discussed in Streets (1996b).

Figure 8 shows excess deposition for the BCT scenario. Compared to the ACT scenario the increase in emissions from the large point sources results in a situation whereby many parts of eastern China face excess deposition of more than two grams per square meter per year, with peak exceedances in the Sichuan and Shanghai provinces of about ten grams. Consequently, it can be concluded that in the long run a strategy relying solely on control technologies with modest removal efficiencies will not be able to preserve important agricultural areas from serious excess deposition. This scenario maintains the present (1990) levels of risk in Japan and South Korea.

The advanced control technology scenario made a step towards increasing cost-effectiveness in comparison to the best available technology scenario by selecting only the most effective measures. A further reduction of costs, without increasing environmental damage, could be achieved by directing advanced control measures to ecologically sensitive areas and relaxing control requirements at less sensitive locations. It should be mentioned that China is currently exploring similar approaches by requesting only power stations in ecologically sensitive regions to reduce emissions (rational siting of plants, Zhao *et al.*, 1995). As an illustrative example, Amann and Cofala (1996) explored a scenario for China that applies advanced emission control measures to only those provinces where significant excess deposition would occur without such measures (see Table 3). Emissions and control costs for these three countries in the LACT scenario are shown in Table 4. These results show that lower emissions, and thus substantial environmental protection, could be achieved at 70% of the cost of the BCT or ACT scenarios.

Furthermore in some cases a few sources dominate the cause of acid deposition in a region. For example one of the 'hot spots' of sulfur deposition, with exceedance of critical loads of more than ten grams sulfur/m2/year, occurs in the Chinese Sichuan province. Table 5 shows that specific point sources make a significant, and often dominant, contribution to local deposition (e.g., the Chengdu power station contributes about 30 percent of total deposition to grid 105 degrees East, 30 degrees North). Consequently, measures that focus on a few specific sources could significantly improve the local situation.

Table 3.Regional emission control strategies for the Local ACT scenario in China.

NO CONTROL	ADVANCED EMISSION CONTROL (ACT)
China:	
Fujian Guandong-Hainan Guanxi Hebei-Anhui-Henah Inner Mongolia North-eastern plain, Heilongjiang Shenyang West Tibet-Quinghai Yunnan	Beijing Chongqing Guangzhou Guyang Guizhou Hubei Hunan Jiangsu Jianxi Shanghai Shaanxi-Gansu Shandong Shanxi Sichuan Taiyuan Tianjin Wuhan Zhejiang

Table 4.Emissions and control costs in 2020 for China in the LACT scenario

	Emissions(thousand tons SO2)			Costs, million US $		
	LACT	BCT	ACT	LACT	BCT	ACT
China	37904	38124	29932	8505	12609	12063

Table 5.
Contribution of sulfur deposition in a receptor location in Sichuan
for the reference scenario for the year 2020 in milligrams sulfur/m2/year
(note that those power stations designated with an N
are only foreseen for the year 2020 and do not yet exist!)

Receptor in Sichuan (30_ N, 105_ E)

Area Source Location:	Sulfur Dep.	Large Point Sources:	Sulfur Dep.
China, Sichuan	10324	China, LPS N25 (Chengdu)	5901
China, Chongqing	1085	China, LPS N24 (Jianqou)	993
China, Yunnan	115	China, LPS 56 (Baima)	189

China, Shaanxi-G.	47	China, LPS 4 (Chongqing)	129
China, Guizhou	94	China, LPS N1 (Luohang)	118
China, Guiyang	28	China, LPS N65 (Douba)	89
China, West Tibet	16	China, LPS N66 (Huayinshan)	65
China, Hubei	16	China, LPS N59 (Xigu)	13
China, Hebei	8	China, LPS 11 (Qinzhen)	13
China, Hunan	5	China, LPS N22 (Jingyuan)	11
China, Other Provinces	11	China, 10 other LPS	27
India, all sources	6		
TOTAL DEPOSITION	19303	Critical Load (25 percentile)	4035

Another way to limit environmental impacts would be to consider relocating coal power stations which make significant contributions to excess deposition in sensitive ecosystems in the baseline scenario, to less sensitive regions. As an illustration Amann and Colfalo (1996) evaluated the impact of relocating four sources planned for construction in the heavily polluted region of the Sichuan province to the northern part of the country. Even under the assumption that the relocated power stations would not be equipped with desulfurization technologies, excess deposition in the hot spots declined compared to the baseline reference scenario. For instance, in the Sichuan province excess deposition in the grids affected by the moved sources decreased by about five to six g/m2-yr, whereas, due to the large tolerance of acid deposition of the ecosystems in the new locations, no major areas would experience excess deposition as a result of this measure.

All the scenarios discussed above are based on certain assumptions about the development of the economies and of energy intensities. However, the volumes and the structural composition of energy supply also have a critical influence on the level of emissions. These contributing factors imply that not only will emission levels be crucially dependent on the energy scenario, but also that energy policies promoting energy efficiency and use of cleaner fuels are important instruments to reduce pollution and pollution control costs.

To illustrate this fact calculations were performed using a control strategy based on the energy efficiency pathway (HEF scenario). As discussed in Streets (1996b), the HEF pathway results in a 40% decrease in SO_2 emissions in Northeast Asia, relative to the unabated BAS emission. Consequently, emission control strategies based on the energy efficiency pathway provide better protection for the ecosystems than would result from the base case. The excess sulfur deposition for this HEF case is shown in Figure 8. As expected the exceedance map shows that the vulnerability of Northeast Asia under this scenario is substantially improved relative to the BAS situation, and accomplishes improvements similar (but no quite as effectively) as those for the BCT scenario. Combining energy efficiency with controls as discussed above is an obvious strategy which would yield long term benefits.

Finally it is illustrative to look at the impact of the various control strategies on the deposition at a specific receptor. We chose a receptor located in southern Honshu, Japan. The annual calculated sulfur deposition for the various scenarios at this site are summarized in Table 6. This particular site is presently receiving an excess deposition of ~100 mg-S/m2/yr (calculated as the difference between the total deposition and the 5% critical load). Under the BAS assumptions, by the year 2020 it would be receiving an excess deposition of nearly 10 times the present levels! Only the BAT and ACT scenarios are projected to reduce future depositions at this site below the critical levels. Another interesting point is that the scenarios also influence the source-receptor relationships. Also shown in Table 6 are the sources of the deposition at this receptor location for the various scenarios. At present Japanese emissions contribute ~17% to the deposition at this site. Under the BAS scenario, Japan's contribution decreases by a factor of 2, while the contributions from China and South Korea increase. Under the BCT and ACT scenarios the importance of Chinese emissions grows to nearly 50%, while that due to South Korea sources decreases to ~25%. Under the BAT scenario the contribution due to Japanese sources increases (to ~25%), but China and South Korea still contribute 22% and 53%, respectively.

Table 6.Sulfur deposition (in mg-S/m2/yr) at a receptor location at the southern tip of Honshu, Japan in 2020 for the various scenarios discussed. For reference, 1990 values are also presented.

	1990	BAT	ACT	BCT	EFF	BAS
China	125	34	163	230	257	344
Japan	81	38	94	94	66	98
S. Korea	267	82	84	123	494	754
N. Korea	10	2	2	20	25	38
Volcanoes	33	33	33	33	33	33
Total Deposited	516	189	376	500	875	1267
5% Critical Load	415	415	415	415	415	415
Percentage contribution to anthropogenic deposition as a function of the various emission scenarios discussed.						
China	26	22	48	49	31	28
Japan	17	24	27	20	8	8
S. Korea	55	53	24	26	59	61
N. Korea	2	1	1	4	3	3

What Conclusions Can We Draw for Northeast Asia ?

The present situation in Northeast Asia is that high levels of acidic compounds, predominately sulfate and nitrates, are being deposited throughout the region. The levels of acid deposition are sufficiently high to put ecosystems at risk (as estimated by critical loads for Asia) in vast regions including southern China, South Korea, Taiwan, and southern Japan. The situation would be worse if it were not for the fact that Northeast Asia has high levels of wind blown soils which neutralize an appreciable fraction of the strong acids. Model calculations suggest that transboundary transport already contributes to acid deposition in Korea and Japan.

This situation most likely will change dramatically as a consequence of the very high economic and population growth rates of the region. The expansion of fossil fuel energy systems, combined with a major fuel shift to indigenous coal, will undoubtedly result in a significant increase in atmospheric emissions for the Asian countries. Substantial portions of these emissions will be transported by winds hundreds of kilometers from their source. To help quantify and anticipate environmental impacts associated with these emissions it is imperative that we develop a greater understanding of the mechanisms of long range transport of pollutants in Asia. Increased monitoring and modeling activities will be needed, which could be conducted as regional and/or bi-lateral initiatives. These activities are necessary because there is considerable uncertainty associated with modeling sulfur deposition in a region as large as Asia. The lack of a comprehensive observation network prevents us from rigorously evaluating model performance in Northeast Asia. This situation will improve as a result of the Japan JEA-lead activity on establishing an acid deposition monitoring network for Asia. This network has been discussed at four expert meetings and is now in the implementation phase (JEA, 1995). Furthermore, the modeling activity discussed in this paper as well as most other attempts, make use of parameterizations which have been derived based on modeling studies at the mid-latitudes in North America and Europe. There is still uncertainty as to how well these values capture the wide variations in geographical features and latitudinal variations associated with Asia. Although extensive experience can be drawn from Europe and North America, the Asian situation is sufficiently different in terms of mixes of pollutants, meteorology, etc., that what we need is Asian-specific information on the mechanisms of acid deposition and long range transport. There is a clear need to conduct more model comparisons and fundamental studies to better determine the most suitable parameters for use in modeling studies in Northeast Asia. Until such studies are done all source-receptor relationships must be treated with extreme caution. Moreover, the present estimates are not yet sufficiently robust to serve as the foundation for policy analysis related to allocation of responsibility and liability for transboundary air pollution in the Northeast Asian region. Conversely, the models already demonstrate clearly the need to address the issue of acid deposition at the source - whatever the ultimate transboundary distribution of the acid rain precursors.

The present trends in energy consumption in the region impose significant environmental threats to a variety of ecosystems in large parts of Asia. Within the next two to three decades, as the regional SO2 emissions increase, sulfur deposition levels are anticipated which are higher than those observed in Europe and North America during the 1970s and 1980s, and in some cases will most probably exceed those observed previously in the most polluted areas in central and eastern Europe. This increase in SO2 emissions will severely threaten the sustainable basis of many natural and agricultural ecosystems in the region. Taking the critical loads as an indicator for sustainable levels of acid deposition, future sulfur deposition will exceed critical loads by more than a factor of ten in wide parts of Asia. These levels of sulfur deposition would cause significant changes in the soil chemistry over wide areas in Asia, affecting growing conditions for many natural ecosystems and agricultural crops. Furthermore, ambient levels of SO2 would exceed WHO health guidelines not only in cities, but also in many rural regions. If no countermeasures are taken, our results suggest a degradation of the environmental quality to unprecedented levels.

There are a variety of measures that could be taken to reduce SO2 emissions and thereby avoid widespread excess deposition in the region. Advanced emission control technologies could reduce emissions below current levels even in a high growth energy scenario, albeit at extremely high costs. Illustrative scenarios demonstrate the potential for an increase in the cost-effectiveness of strategies if measures are focused on specific fuels, technologies, economic sectors, emission sources or ecologically sensitive regions. All of these activities make a difference. Energy planning is also an important factor for controlling adverse environmental effects, in particular acidification. The development of carefully designed energy systems is of particular importance for controlling emissions in those countries considering an expansion or replacement of the present energy infrastructure.

However, the situation in Northeast Asia is probably bleaker than we have discussed. Most of this paper has focused on sulfur as the main component of acid deposition. While this is generally true in this region, the contribution of nitric acid is rising along with the increase in NOx emissions as discussed in Streets (1996b). The attendant increase in NOx emissions will not only lead to an increase in acid deposition, but will also pose additional environmental concerns through increases in ambient ozone levels. Increasing levels of ozone have significant environmental impacts, including human health and reduction in crop yields. Initial work by Chameides et al. (1994) have suggested that the increase in NOx emissions and fertilizer use in Northeast Asia, may lead to ozone levels sufficiently high to threaten rice, wheat and corn production. Ozone, like acid deposition, is a regional problem, which will require regional cooperation and emission reduction policies to control.

Ammonia presents still another concern. Because of the predominately rural and agricultural nature of large portions of Northeast Asia, emissions of ammonia, associated with livestock and the intensive use of fertilizers to meet the growing demand for food, are increasing even more rapidly than emissions of SO_2 and NO_x (Galloway, 1995). As discussed previously, ammonia in rainwater acts as a base, neutralizing the strong acids, and elevating the pH of precipitation. However, after it is deposited on soils biochemical processes cause ammonia to act as a strong acidifying agent. Thus, ammonia may be masking the extent of the problem of acid deposition in Asia as measured by pH alone, and may actually be contributing significantly to ecosystem damage (as is the case in the Netherlands). The role of ammonia in this regard is not yet well characterized in Northeast Asia, but its study should be given high priority. The inclusion of ammonia into the acid deposition arena requires the simultaneous consideration of energy and food security policies.

Finally, the regional aspect of acid deposition pose a significant challenge to the region. The Asian situation is much different than that in Europe and USA when they encountered acid deposition as a significant problem. In Europe, the UN Economic Commission for Europe (UNECE) provided a forum for countries to discuss the problem and develop policies aimed at reducing sulfur and nitrogen emissions. Under the auspices of UNECE the Convention on Long Range Transport of Air Pollutants (LRTAP) was first signed in 1979. In addition, there were active collaborations and joint research activities among the countries looking at various aspects of the problem providing scientific input into the deliberations. Both research and policy fora will need to be further developed in Asia to address the challenges presented by these regional environmental problems.

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References

Akimoto, H. and Narita, H. "Distribution of SO2, NOx, and CO2 Emissions from Fuel Combustion and Industrial Activities in Asia with 1° x 1° Resolution", *Atmospheric Environment,* 28 (2), 213-225 (1994).

Amann, M., and J. Cofala, Chapter 7, Rains-Asia: "An Assessment Model for Air Pollution in Asia", final report to The World Bank, December (1995).

Amann M., Klaassen G., Schoepp W. "Closing the Gap Between the 1990 Deposition and the Critical Sulfur Deposition Values. Background Paper for the UN/ECE Task Force on Integrated Assessment Modelling", UN/ECE, Geneva, Switzerland, (1993).

Arndt, R. L. and Carmichael, G. R. "Long-Range Transport and Deposition of Sulfur in Asia." *Water, Air and Soil Pollution*, Vol. 85, 2283-2288 (1995).

Arndt, R. L., Carmichael, G. R., and Roorda, J. M. "Seasonal Source-Receptor Relationships in Asia.", in press *Atmospheric Environment*. (1996b).

Arndt, R. L., Carmichael, G. R., Streets, D. G., and Bhatti, N. "Sulfur Dioxide Emissions and Sectorial Contributions to Sulfur Deposition in Asia." *Atmospheric Environment.*, in press (1996).

Ayers, G. and Hara, H. *Acid Deposition Assessment Report.* Report to World Meteorological Organization (1994).

Carmichael G.R. and Arndt R.L. Long range transport and deposition of sulfur in Asia, in *An assessment model for acid rain in Asia,* Report from the World Bank sponsored project "Acid rain and emission reduction in Asia" (1995).

Carmichael, G. R., Ferm, M., Adhikary, S., Mohan, M., Hong, M.-S., Chen, L., Fook, L., Soedomo, M., Lui, C. M., Zhao, D., Tran, G., Ahmad, J., Suksomsank, K., Chen, L.-L., Arndt, R. L. "Observed Regional Distribution of Sulfur Dioxide in Asia", *Water, Air and Soil Pollution*; Vol. 85, pp. 2289-2294 (1995).

Carmichael, G.R., L.K. Peters, and R.D. Saylor. "The STEM-II regional scale acid deposition and photochemical oxidant model: I. An overview of model development and applications", *Atmos. Environ., 25A*, 2077-2090 (1991).

Chang, Y., R. Arndt, G. Calori, G. Carmichael, D. Streets, and Haiping Su "Air Quality Impacts as a Result of Changes in Energy and Land Use in Chinaís Jiangsu Province", in press *Atmos. Environ.*, July (1996).

Chameides, W., P. Kasabhatla, J. Yienger, and H. Levy, " Regional Ozone Pollution and World Food Production ", *Science*, 264, 74-77(1994).

Cofala, J. Personal Communication (1995).

CRIEPI "Data Report of CRIEPI Acidic Deposition Project, 1987-1900", Central Research Institute of Electrical Power Industry Report, Tokyo, Japan (1992).

CRIEPI "Acidic Deposition in East Asia - International Workshop on Acidic Deposition in East Asia" Central Research Institute of Electrical Power Industry Report, ET93002 (1994).

Florig, H. K. "The Benefits of Air Pollution Reduction in China", Submitted to *Environmental Science and Technology*, July 1995.

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., Sherestha, R., Streets, D., Zhao, D. "Energy Use, Emissions, and Air Pollution Reduction Strategies in Asia." *Water, Air and Soil Pollution*, Vol. 85, 2277-2282 (1995).

Fujita, S. "An Estimation for Atmospheric Sulfur Budget over the Japanese Archipelago", *Environmental Science*, Vol. 9, No. 2 (1996).

Galloway, J. "Acid Deposition: Perspectives in Time and Space", *Water Air and Soil Pollution*, Vol. 85, 15-24 (1995).

Hara, H. "Acid Deposition Chemistry in Asia", *Bull. Inst. Public Health*, Vol. 42, 426-437 (1993).

Hettelingh J.-P., Sverdrup H. and Zhao D. "Deriving critical loads for Asia", *Water, Air and Soil Pollution*, Vol. 85, pp. 2565-2570 (1995).

Hettelingh, J-P. Guidelines for Design of Acid Rain Policy for Asia, pp. 123-145, Proceedings of the Second Annual Workshop on Acid Rain in Asia. AIT Bangkok, (1991).

Hordijk, L., Foell, W., and Shah, J. *Chapter 1. RAINS-ASIA: An Assessment Model for Air Pollution in Asia*, Phase-I Final Report (1995).

Hoffman, S. *Global Trade and Transportation*, 114: pp. 43, (1994).

Huang, M., Wang, Z, He, D., Xu, H., Zhou, L. "Modeling Studies on Sulfur Deposition and Transport in East Asia." *Water, Air and Soil Pollution*, Vol. 85, 1921-1926 (1995).

Ichikawa, Y. and Fujita, S., "An Analysis of Wet Deposition of Sulfate using a Trajectory Model for East Asia", *Water, Air and Soil Pollution*, Vol. 85, 1927-1932 (1995).

IUFRO (International Union of Forest Research Organizations), Resolution über Maximale Immissionsraten zum Schutze der Wälder. Fachtagung Laibach/Jugoslawien 18 - 23 September 1978.

JEA, Expert Meetings on Acid Deposition Monitoring Networking East Asia.

Katatani, N., "Some comparison of the RAINS-Asia deposition model with observations and other model calculations", private communications, 10 pages, (1996).

Katatani, N., N. Murao, S. Okamoto, N. Ono and K. Kobayashi, "A modeling study on acid deposition and secondary aerosols in eastern Asia", Proceedings of the 9th World Clean Air Congress (Montreal), Vol 3, IU-16B.11 (1992).

Kato, N., and Akimoto, H. "Anthropogenic Emissions of SO2 and NOx in Asia." Third Annual Conference on Acid Rain and Emissions in Asia, Bangkok, Thailand, 18-21 Nov., 1991

Khemani, L. T., Momin, G. A., Prakasa Rao, P. S., Safai, P. D., Singh, G., and Kapoor, R. K., "Spread of Acid Rain Over India." *Atmospheric Environment*, Vol. 23, No. 4, 757-762 (1989).

Kotamarthi, V. and Carmichael. G. "The Long Range Transport of Pollutants in the Pacific Rim Region." *Atmospheric Environment,* Vol. 24A, 1521-1534 (1990).

Mage, D., Ozolins, G., Peterson, P., Webster, A., Orthofer, R., Vanderweed, V., Gwynne, M. "Urban Air Pollution in Megacities of the World.", *Atmospheric Environment*, Vol. 30, No. 5, pp. 681-686 (1996).

Merrill, J. R. Bleck and Avita, L. Modeling Atmospheric Transport to Marshall Island. *Journal of Geophysical Research,* Vol.90, pp. 12927-12936 (1985).

Mohamed, M. and Kamsah, M. Z. "A Year Long Study on Acid Rain and Levels of Nitrate and Sulfate in the Rain Water of the Klang Valley." Proceedings of the International Conference on Regional Environment and Climate Change in East Asia, National Taiwan University, Nov. 30 - Dec. 3, 1993.

Murano, K. "Activity of JEA for East Asian Acid Precipitation Monitoring Network". Presented at Workshop on Acid Rain Network in South, East, and Southeast Asia, Malaysia, May 17-19, 1994.

Phadnis, M., G. Carmichael, Y. Ichikawa, and H. Hiroshi, "Evaluation of Long Range Transport Models for Acidic Deposition in East Asia", submitted to *Atmos. Environ.*, July (1996).

Qi, L., Hao, J., and Lu, M. "SO2 Emission Scenarios of Eastern China.", *Water, Air and Soil Pollution*, Vol. 85, pp. 1873-1878, (1995).

Robertson, L., Rodhe, H., and Granat, L. "Modelling of Sulfur Deposition in the Southern Asian Region", *Water, Air and Soil Pollution*; Vol. 85, pp. 2337-2334 (1995).

Rodhe, H., and Granat, L. "An evaluation of sulfate in European precipitation 1955-1982", *Atmospheric Environment,* 18, 2627-2639 (1984).

Rodhe, H., J. Galloway, and D. Zhao. "Acidification in Southeast Asia - Prospects for the Coming Decades." *Ambio*, Vol. 21, No. 2, 148-150 (1992).

Sato, J., Satomura, T., Sasaki, H., Muraji, Y. "A Coupled Meteorological and Long-Range Transport Model, and its Application to the East Asian Region." Submitted to *Atmospheric Environment* (1995).

Sekiguichi, K., "Acid Air Pollutants and Their Effects on the Environment", *Annual Report of Gumma Research Institute of Public Health and Environmental Science*, 19, 30-43 (1987).

Sharma, M., McBean, E. A., and Ghosh, U. "Prediction of Atmospheric Sulfate Deposition at Sensitive Receptors in Northern India", *Atmospheric Environment*, Vol. 29, pp. 2157-2162 (1995).

Shrestha, R. M. and Bhattacharya, S. C. "Coal use in Electricity Generation in Asia and Emission Control Options", Proceedings from the Third Annual Conference on Acid Rain and Emissions in Asia, 18-21 Nov., 1991, Bangkok, Thailand (1991).

Siddiqi, T. A. "Carbon Dioxide Emissions from the Use of Fossil Fuels in Asia: An Overview" *Ambio*, Vol. 25, No. 4, pp. 229-234 (1996).

Streets, D., Carmichael, G. R., and Arndt, R. L. "Sulfur Dioxide Emissions and Sulfur Deposition from International Shipping in Asian Waters", *Atmospheric Environment*, in press (1996).

Streets, D., "Energy and Acid Rain Projections for Northeast Asia", study paper for the Energy, Security, and Environment in Northeast Asia Project (1996b).

Walsh, M. P. "Worse than feared", *Acid News* Vol. 3 (1996).

Wang, W. and Wang, T. "On the Origin and the Trend of Acid Precipitation in China" *Water, Air, and Soil Pollution*, Vol. 85, 2295-2300 (1995).

Welpdale, D. "Sulfur and Nitrogen Budgets around the World", WMO Report (1996).

WHO (World Health Organization), Environmental Health Criteria 8 - Sulfur Dioxide. Geneva, Switzerland (1979).

Xie S, J. Hao, Z. Haou, L. Qi, and H. Yin "Assessment of critical loads in Liuzhou, China using static and dynamic models", *Water, Air and Soil Pollution* 85, 2401-2406 (1995).

Zhao D., Mao J., Xiong J., Zhuang X., Yang J. "Critical Load of Sulfur Deposition for Ecosystem and its Application in China", Research Center for Eco-Environmental Sciences, Academia Sinica, Beijing, China, pp.23 (1995).

Zimmerman, T., Lawrence, S., Palmer, B., and Moulier, P. B. "China takes a deep breath." *U.S. News & World Report*, Sept. 9, 1996.

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