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Urban Air Quality and Health in China

Chaoyang Peng, Xiaodong Wu, Gordon Liu, Todd Johnson, Jitendra Shah and Sarath Guttikunda

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Summary. Urban air pollution is one of the most visible environmental problems in China. In this paper, we use emission inventory data to assess the air quality and health effects in the Chinese city of Shijiazhuang. A spatial model is developed to identify the sources of emissions and to estimate population exposure to high ambient concentrations. Dose-response functions are used to quantify the impact on human health. Our results show significant health costs associated with Shijiazhuang's high concentration of sulphate, a fine particulate matter originating mainly from coal consumption. Policy implications are explored by evaluating alternative pollution control options. The use of cleaner coal is found to be the most cost effective in improving urban air quality and reducing human exposure.

1. Introduction

Ensuring a liveable urban environment is a priority in China's rapid urban development. More than 450 million of China's 1.3 billion population are now living in urban areas where over 70 per cent of China's gross domestic product (GDP) are generated and where the environmental impacts of concentrated human activities are felt the most. Air pollution is perhaps the most visible environmental problem in China's urban life. High ambient concentrations of ground-level emissions cast a hazy veil over the urban landscape and cause alarming damage to public health. A recent survey by the State Environmental Protection Administration (SEPA, 2001) found that two out of three cities in China failed to meet the residential ambient air quality standard, resulting in large population exposure to health risks such as chronic bronchitis, pulmonary heart disease and lung cancer.[1] Respiratory diseases are a leading cause of premature deaths in China. The World Bank (1997) estimated that air pollution cost China's economy more than 7 per cent of GDP in 1995, largely in health damage.

Air pollutants involve a complex mixture of small and large particles of varying origin

Chaoyang Peng is in Chapel Hill, North Carolina, USA. Fax: 919 42 3186. E-mail: peng@alumni.princeton.edu . Xiaodong Wu is in the Department of Economics, University of North Carolina at Chapel Hill, Gardner Hall 304, Chapel Hill, NC 27599–3305, USA. Fax: 919 966 4986. E-mail: wux@email.unc.edu . Gordon Liu is in the Department of Pharmaceutical Policy and Evaluation Sciences, University of North Carolina at Chapel Hill, Beard Hall 205, Chapel Hill, NC 27599–0001, USA. Fax: 919 966 8486. E-mail: ggliu@unc.edu . Todd Johnson is in the Environment Department, The World Bank, 1818 H Street NW, Washington, DC 20433, USA. Fax: 202 522 2130. E-mail: tjohnson@worldbank.org . Jitendra Shah is in the Environment and Social Development Section, East Asia and Pacific Region, The World Bank, 1818 H Street NW, Washington, DC 20433, USA. Fax: 202 522 1664. E-mail: jshah@worldbank.org . Sarath Guttikunda is in the Center for Global and Regional Environmental Research, University of Iowa, 204 Iowa Advanced Technology labouratories, Iowa City, Iowa 52242–1000, USA. Fax: 319 335 3337. E-mail: sguttiku@cgrer.uiowa.edu . The authors are grateful to Ken Small and two anonymous referees for their helpful comments and suggestions. The authors also thank Yuebin Li and his colleagues in the Shijiazhuang Municipal Environmental Protection Bureau, Fahe Chai, Fan Meng, Duan Ning and Jun Xu in the Chinese Research Academy of Environmental Sciences, and Guomei Zhou of the State Environmental Protection Administration in Beijing for their valuable assistance. The findings, interpretations and conclusions expressed in this paper are entirely those of the authors and should not be attributed in any manner to the affiliated institutions.

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and chemical composition, including fossil fuel emissions, industrial fugitive dust, wind-blown soil and secondary pollutants from atmospheric chemical processes. The health effects of air pollutants are strongly linked to particle size. Scientific studies suggest that fine particulate matter—less than 10 microns in diameter (PM_{10})—is likely to be most dangerous, because such fine particles can be inhaled deeply into the lungs where the clearance time of deposited particles is much longer, increasing the potential for adverse health effects. The most common airborne fine particles in China are sulphates emitted from coal combustion, which are aerosols converted from sulphur dioxide (SO_2) when condensed in the atmosphere.

Fine particulate matter is also the worst in terms of the frequency and degree of non-compliance with air quality standards in Chinese cities. Available data suggest that fine particulate matter makes about 60 per cent of China's total suspended particulates (TSP). Ambient TSP concentrations have been consistently monitored in China and serious TSP levels are found to be prevalent in all cities. The average TSP level in large cites in 1998 was 324 micrograms per cubic metre ($\mu g/m^3$) compared with the standard of 200 $\mu g/m^3$. Limited monitoring data on PM_{10} in the same year show even greater violation of the air quality standard by PM_{10}. The concentration levels of other major pollutants such as nitrogen oxide (NO_x) exceeded their limits moderately.[2] While PM_{10} is a better predictor of health effects than TSP, most studies have based assessments on TSP because the effort to monitor PM_{10} has only just begun in China (World Bank, 1997 and 2001).

This paper presents a case study to assess the environmental health impact of fine particulate matter concentrations in a Chinese city. A spatial model is used to estimate the ambient concentrations based on emission inventory data, which are more readily available than data on ambient concentration. This modelling approach also overcomes a common problem in interpreting ambient monitoring data collected in urban areas in China. Rapid urbanisation in the past decade has expanded China's built-up urban areas by 50 per cent, but the number and location of urban air quality monitoring stations have remained unchanged. The monitoring data thus often do not reflect the air quality of the changing urban pattern in a city as a whole but just the inner city. The spatial model used in this paper is flexible in defining a study domain and thus captures conditions both within and beyond the city boundaries.

The case study is for Shijiazhuang, an industrial city 275 kilometres south-west of Beijing. Air quality in Shijiazhuang has been deteriorating in recent years, making it currently the third-worst polluted city in China. We focus on sulphates because they have been identified as the primary component of inhalable particulate matter in China and are known to be a chief culprit for health damage. Also sulphates can be traced to the source of emissions, mainly from the combustion of fossil fuels. We use emission data collected in Shijiazhuang to analyse emission sources and develop a spatial model to assess population exposure to sulphate concentrations. Dose-response functions are then used to quantify the impact of exposure on human mortality and morbidity.

2. Modelling Methodology

The analytical tool used in this study is the urban branching atmospheric trajectory (UrBAT) model (Calori and Carmichael, 1999). This is a three-dimensional multilayered Lagrangian model capable of estimating ambient concentrations at the urban scale. The model is a modified version of the atmospheric transport and deposition (ATMOS) model (Heffter, 1983; Arndt *et al.*, 1998) developed as part of the regional air pollution information system for Asia (RAINS-Asia). This is a software package developed to trace the causes and consequences of air pollution across 23 countries and 94 sub-regions in Asia (IIASA, 2001; Shah *et al.*, 2000). To capture the impact of air pollutants from distant sources, the resolution used in RAINS-Asia is typically 1° by 1° in latitude and longitude to accommodate analysis at a

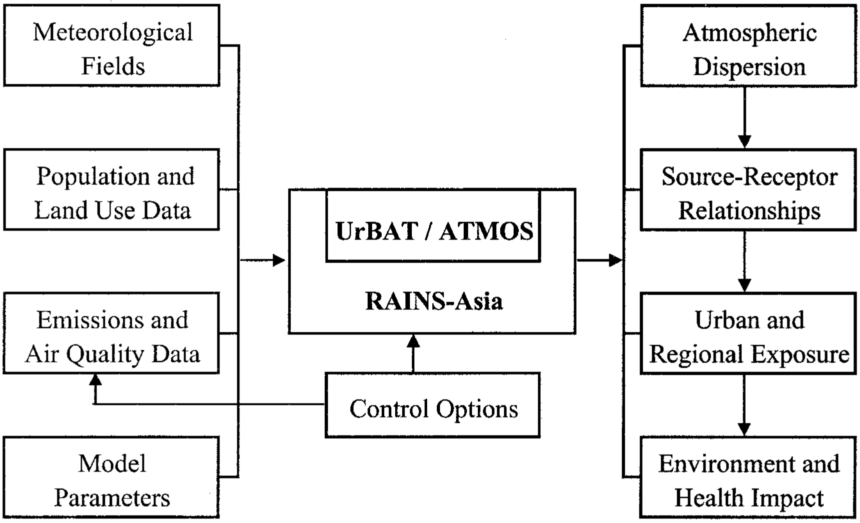

Figure 1. A framework for modelling urban air pollution.

regional scale. UrBAT improves upon ATMOS to provide higher resolution analysis, using much of the same data. In this study, UrBAT is calibrated to the resolution of 0.01° by 0.01°, equivalent to approximately 1 kilometre by 1 kilometre.

Figure 1 presents the schematics of the modelling framework. Meteorological fields, terrain features, population density and emission sources are all incorporated as inputs into the UrBAT and ATMOS models, to generate spatial patterns of pollution dispersion and population exposure. UrBAT and ATMOS trace emissions from sources to receptors in the following manner

$$\mathbf{R}_i = \Sigma_j \mathbf{T}_{ij} \mathbf{E}_j$$

where, $\mathbf{R}_i$ is a vector of ambient concentrations in area i, $\mathbf{T}_{ij}$ is a transfer matrix that determines the proportion of net emissions from area j transported to area i, and $\mathbf{E}_j$ is a vector of emissions from area j.

Because of its fine resolution, UrBAT can thus relate emission sources to ambient concentrations within an urban area. In contrast, ATMOS can trace the sources and consequences of air pollutant transport and transformation between regions.

Emission plumes are modelled as puffs released in a given time-interval and the trajectory of each puff is tracked in the modelling domain. The UrBAT model separates the vertical dimension into two layers (mixing layer and upper layer) during the day and three layers (surface layer, boundary layer and upper layer) at night, as determined by the vertical temperature profile. The model allocates emissions in different layers according to the source type and the hour of the day. Area emission sources (small industries, residential and mobile sources) are released into the mixing layer during the day and into the surface layer at night. Elevated sources such as high chimney emissions are also released into the mixing layer during the day, but at night they are branched into both the surface and boundary layers. (In the ATMOS model, elevated emissions are dispersed entirely within the boundary layer at night, so the UrBAT model better captures the night-time vertical mixing.) Further details are documented in Arndt *et al.* (1998) and Calori and Carmichael (1999).

In this application of UrBAT, gaseous sulphur dioxide is assumed to emit from each source in the study domain and chemical conversion of sulphur dioxide to aerosol sulphate follows a simple first-order rate constant. The meteorological data used to disperse emissions in different layers are obtained from the NCEP/NCAR reanalysis project (Kalnay *et al.*, 1996). Information on wind vector, precipitation rate, mixing height, surface pressure, surface temperature and surface heat sensitivity are extracted from this data source for the study domain.

Distant emissions from outside the urban area are modelled to form background concentrations. This is important as urban air quality is affected not only by emissions from within the city, but also by remote sources. In the case of Shijiazhung city, there are a number of large point sources (thermal power plants, cement and lime factories) in the greater Shijiazhuang region upwind to the north-west of the city. In addition, long-range transboundary emissions from neigbouring provinces are also considered by extracting information from the RAINS-Asia database (IIASA, 2001).

By combining this model of atmospheric dispersion with a population profile of the city, UrBAT results are used to calculate population exposure and to estimate mortality and morbidity rates based on dose-response functions. Control options to alleviate the impacts of air pollution are then evaluated by simulating emission reductions and the consequent improvements in urban ambient concentrations.

Applications to a number of cities in China, including Beijing (Calori and Carmichael, 1999) and Shanghai (Streets *et al.*, 1999), suggest that UrBAT/ATMOS is quite robust in its estimation of air quality for the purpose of human health and environmental impact assessment. In this study, air pollution data collected from World Bank missions to the city of Shijiazhuang in 2000 and 2001 are used as input to estimate ambient concentrations and to assess health and environment impacts. Beyond that, the existing model parameters for UrBAT/ATMOS (Version 2.3) and RAINS-Asia (Version 7.52) are used unless otherwise cited.

3. Shijiazhuang

Shijiazhuang city, the capital of Hebei province, is home to more than 1.5 million urban residents in an area about 250 square kilometres. It is part of the Shijiazhuang ‘municipality’, an administrative unit comprising 17 counties and 22 towns in Hebei province: the municipality is 61 times larger in area but has only one-tenth the population density of the city. Serious environmental problems in the greater Shijiazhuang region include water quality and land degradation. This paper, however, focuses just on urban Shijiazhuang, where air pollution is the major environmental concern.

Epitomising the rapid urbanisation in China, the Shijiazhuang urban economy has been growing at more than 13 per cent annually in the past decade, driven mainly by industrial development. Energy use has grown at about 10 per cent annually. Like most cities in China, Shijiazhuang relies overwhelmingly on coal to power its urban economy and suffers serious environmental consequences as a result.

Public health statistics suggest that about 4 per cent of the city’s residents suffer from chronic bronchitis, pulmonary heart disease and lung cancer. Y. Li *et al.* (1998) reported that the incidence rates were higher in ‘polluted’ areas than in ‘clean’ areas and the differentials of the incidence rates were 9 cases per 1000 residents for chronic bronchitis, 11 per 1000 for pulmonary heart disease and 8.33 per 100 000 for lung cancer. It has been suggested that high levels of air pollutants are a major contributing factor.

Data collected from the five air quality monitoring stations located in Shijiazhuang trace the city’s ambient concentrations (Figure 2).[3] In 1999, Shijiazhuang’s annual average concentration of TSP was 365 $\mu g/m^3$, far exceeding the residential air quality standard of 200 $\mu g/m^3$. The most health-damaging component of TSP in Shijiazhuang is sulphate originating from coal consumption and formed in the atmosphere through chemical transformation of SO_2. The annual average SO_2 concentration was 130 $\mu g/m^3$, more than twice the limit of 60 $\mu g/m^3$. The seasonal patterns of TSP and SO_2 concentrations reflect both increased coal use for heat-

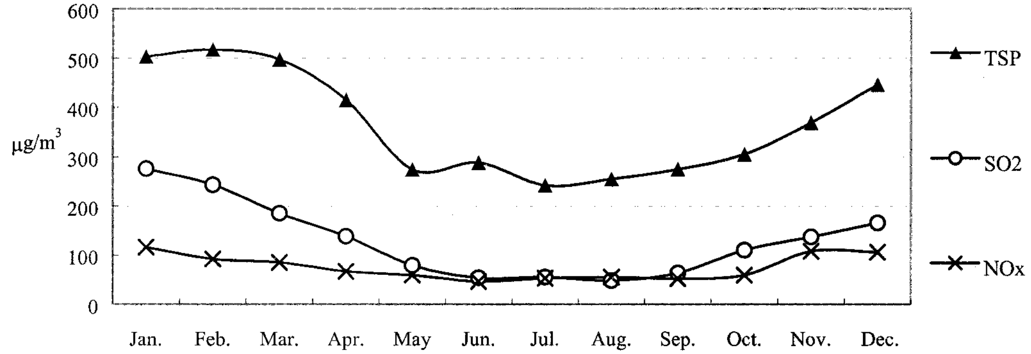

Figure 2. Observed air quality indicators from monitoring data, Shijiazhuang, 1999. *Source:* World Bank mission to Shijiazhuang, August 2000.

ing and reduced air dispersion in winter due to meteorological conditions.

The annual average NO_x concentration was 75 μg/m³, within the standard of 100 μg/m³. However, violations were still observed for winter months. NO_x pollution has been increasing in recent years due to an increase in the number of motor vehicles.

Within the city area, there are currently over 8100 coal-fired boilers and industrial kilns, among which 30 are large point sources with high chimney stacks over 45 metres. Most of the latter are plants that supply electrical power and steam heat to industrial factories. The small sources, by contrast, are mostly in the industrial and residential sectors and have low emission heights. The large number of small area sources has important health implications as they contribute more to ground-level concentrations than the elevated emissions from the power heat plants. The geographical conditions also exacerbate ambient pollution as the city lies at the foot of the Taihang Mountain, which reduces air dispersion above the city.

Coal dominates the fuel mix in Shijiazhuang, with a share as high as 97 per cent in total primary fuel consumption. Despite rapid conversion to natural gas in recent years, gas accounts for only 2 per cent of the city's total fuel use. Fuel oil makes up a mere 1 per cent.[4] To make matters worse, most of the coal consumed in Shijiazhuang has a rather high average sulphur content of 1.5 per cent.

With the assistance of the Shijiazhuang Municipal Environmental Protection Bureau (EPB), detailed energy consumption and emission data for 2000 were collected which enabled tracking energy emissions to their sources by location. Based on emission patterns in Shijiazhuang, the main sources of air pollution are *fine* particulate matter from coal combustion such as soot, flying ashes and especially sulphate. Contributions from other sources such as road and construction dust are small. Given the importance of sulphates for health, we focus attention on the emissions of SO_2, the precursor to sulphate particulates.

A matrix was developed which divides the Shijiazhuang urban area into 1 kilometre by 1 kilometre grid cells, with 19 east–west grids and 13 north–south grids. The spatial distribution of SO_2 emissions in Shijiazhuang in 2000 is presented in Figure 3. Over 55 000 tons of SO_2 were emitted in Shijiazhuang city in 2000. One-third of the emissions were from space-heating boilers scattered in the residential areas and about 15 per cent from small and medium-sized industrial boilers and kilns. The rest are attributed to the large power-and-heat plants.

In addition to emissions from the city area, distant emissions from outside the Shijiazhuang urban area are also estimated. In 2000, the large thermal power plants and cement factories upwind of the city emitted 61 000 tons of SO_2, more than those emitted from within the city area. These emissions are

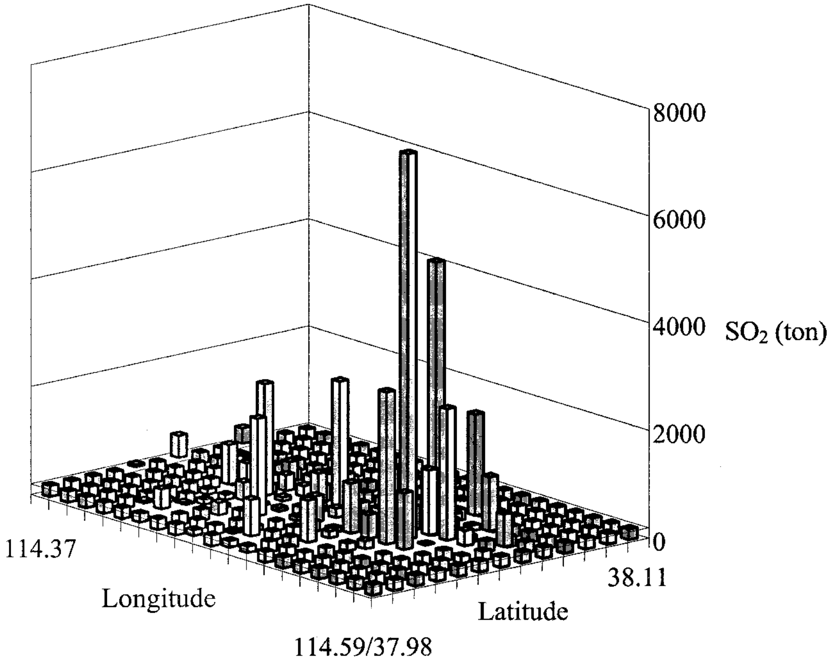

Figure 3. Sulfur oxide emissions in Shijiazhuang, 2000 (1 km by 1 km grid cells. *Source:* World Bank missions to Shijiazhuang, August 2000 and July 2001.

identified by location in the greater Shijiazhuang region and are incorporated in the UrBAT model to estimate their impact on urban air quality in Shijiazhuang city. Also, the long-range transboundary emissions from outside Hebei province are extracted from the RAINS-Asia database (IIASA, 2001) to generate background concentrations for the urban area.

4. Ambient Concentrations and Population Exposure

Figure 4 shows the annual average SO_2 concentrations in 2000 as estimated by UrBAT, incorporating the emissions from all sources. Large areas of urban Shijiazhuang are found to have SO_2 concentrations far above the annual average limit of 60 $\mu g/m^3$, with the north-east area of the city over twice this value. These results are consistent with monitored SO_2 levels: for example, the annual average SO_2 concentration calculated from air samples collected within the second ring road surrounding the city was 112 $\mu g/m^3$ for 2000 (Shijiazhuang Municipal EPB, 2001). The ring roads are shown in Figure 4 to delineate the lay-out of the Shijiazhuang urban area but are not related to the pattern of SO_2 concentrations.

The concentrations of sulphate are presented in Figure 5. The impact of outside sources upwind to the north-west of the city is reflected in the western suburbs, but inside sources from the north-eastern area of the city dominate the sulphate concentration pattern. No guidelines have been set specifically for ambient sulphate concentrations. However, evidence from a study by Dockery *et al.* (1993) shows that for fine particulate matter (PM_{10}), there is a significant relationship between mortality rates and PM_{10} exposure, with a demonstrated 0.8 per cent increase in mortality for each 10 $\mu g/m^3$ annual increase in PM_{10} exposure.

Seasonal simulations indicate that the worst concentration occurs in winter but clears up considerably in spring. This matches the seasonal pattern observed in air quality monitoring data (Figure 2) and also

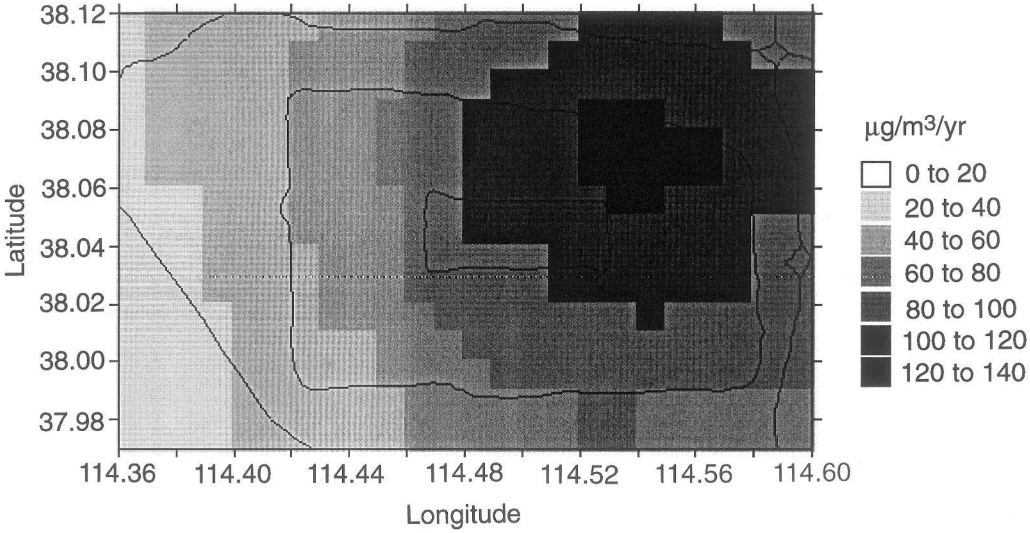

Figure 4: Annual average SO_2 concentrations in urban Shijiazhuang, 2000.

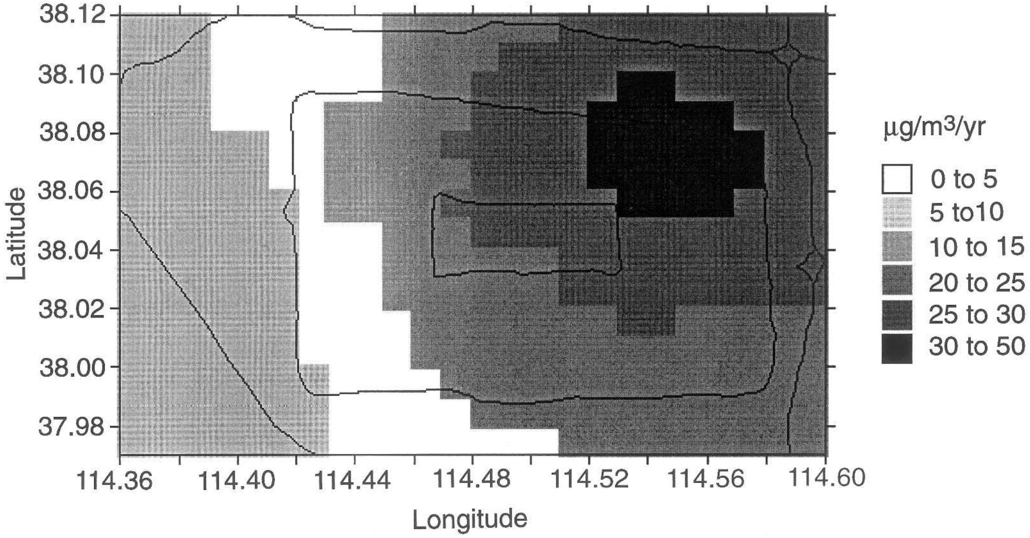

Figure 5: Annual average sulphate concentrations in urban Shijiazhuang, 2000.

confirms that space heating contributes substantially to ambient concentrations in the city. Together with the industrial emissions, the small and dispersed area sources of heating boilers and industrial kilns are identified as the greatest contributors to sulphate concentrations in Shijiazhuang, while the large point sources (power heat plants with high chimney stacks) have less impact.

Source-receptor analysis indicates that emissions from within the city are the primary contributors to urban ambient concentrations, but some concentrations are attributed to emissions from outside the city. Emissions from the elevated large point sources upwind to the north-west of the city are dispersed into the urban surface and their contributions to SO_2 concentrations in the city vary from 5 $\mu g/m^3$ to 17 $\mu g/m^3$ over the urban area. In addition, transboundary emissions from outside Hebei province also form a background SO_2 concentration of about 11 $\mu g/m^3$ for the entire city area.

The spatial pattern of ambient concentra-

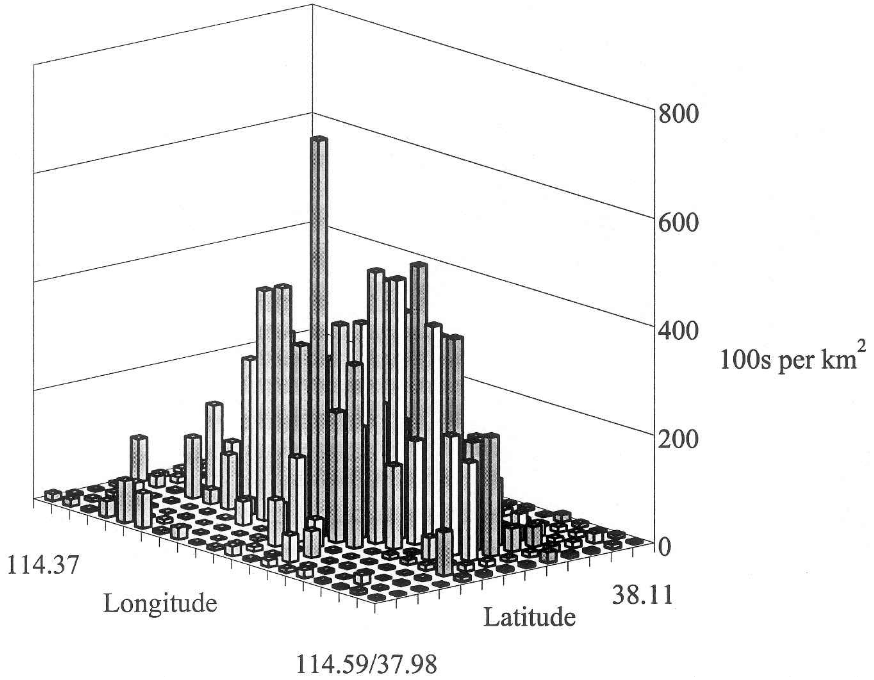

Figure 6. Population density in Shijiazhuang, 2000 (1 km by 1 km grid cells). *Source:* Oak Ridge National Laboratory (2001).

tions shown in Figures 4 and 5 can be superimposed on the population profile of Shijiazhuang to estimate population exposure. We use the LandScan 2000 global population database (Oak Ridge National labouratory, 2001), which apportions subnational census data based on the locations of roads, slopes, land cover and nighttime lights, to develop a population matrix for Shijiazhuang in a 1 kilometre by 1 kilometre resolution (Figure 6). It is estimated that, among the 1.53 million residents in the urban areas of Shijiazhuang in 2000, about 1.4 million (90 per cent) were exposed to various degrees of health-damaging SO_2 and SO_4 concentrations above the threshold levels of 60 $\mu g/m^3$ and 10 $\mu g/m^3$ respectively.

5. Health Impact of Air Pollution

Extensive clinical, epidemiological and toxicological studies provide evidence of the relationships between exposure to ambient concentrations and human health. Correlation among concentrations of different air pollutants, however, makes it hard to separate the effect of any single pollutant species on health. Data complied from the Chinese epidemiological studies suggest that, of the many air pollutants, TSP and SO_2 cause the most extensive damage.[5]

While both TSP and SO_2 are found to be statistically significant in association with health outcomes, only TSP is measured consistently in China and the most significant TSP associated with health problems is PM_{10}, which makes about 60 per cent of TSP in China. PM_{10} is therefore adopted as the key measure for estimating health impact in this study and sulphate is used as the proxy for PM_{10}. Using dose-response functions from both Chinese and international studies (the latter supplement those endpoints that were not measured directly in China), the health impact of high ambient concentrations in Shijiazhuang are estimated following the analytical method outlined by Ostro (1996)

$$dH_i = r_i \cdot POP_i \cdot (dA)$$

where, dH_i is change in population risk of health effect *i*; r_i is rate of change in dose-response function *i*; POP_i is population exposure to health risk *i*; *dA* is change in air pollution.

The economic valuation of health effects is based on estimates of willingness to pay to reduce risks of injury or death. Based on a survey conducted in Chongqing in 1998 by Chinese researchers using the risk-dollar trade-off method to reveal the implied value of statistical life (Li, Schwartz and Xu, 1998), the median value of willingness to pay in a sample of 500 for avoiding a death was US$ 160 000.[6]

Table 1 presents the resulting estimates of health effects of sulphate concentrations, counting only those concentrations above the national ambient standard. It is estimated that 251 premature deaths, 7.7 million cases of acute and chronic morbidity, and 6589 person-years of restricted activities would have been avoided if Shijiazhuang had met the national ambient air quality standards in 2000. Applying the economic valuation numbers, this implies US$40 million for premature deaths and US$31 million for morbidity. The total health cost of US$71 million is about 4.3 per cent of Shijiazhuang's gross domestic product (GDP).

These results are in line with the estimates of health costs by local researchers (Y. Li, *et al.*, 1998). Using incidence rates and survey data, Y. Li *et al.* (1998) estimated the costs of public health associated with air pollution in Shijiazhuang to be RMB 523 million in 1995, equivalent to US$ 63 million converted at the 1995 exchange rate of 8.35 RMB/US$. The higher value estimated for 2000 in this paper may reflect the urban population growth that increases population exposure and also a 25 per cent rise in monitored TSP concentrations (Shijiazhuang Municipal EPB, 2001). However, our estimate is smaller as a share of GDP than that of Y. Li *et al.* (1998) because of Shijiazhuang's rapid real GDP growth in recent years (13.2 per cent per year from 1995 and 2000, according to Shijiazhuang Municipal EPB, 2001).

The sensitivity of the results in Table 1 to key estimation parameters is illustrated in Table 2. One of the sensitive assumptions is that the dose-response functions of PM_{10} are used in this study to estimate the health impact of fine particulate concentrations. A more accurate measure than PM_{10} for fine particulate matter is $PM_{2.5}$—particulate matter of less than 2.5 microns in diameter. Particles larger than $PM_{2.5}$, if inhaled, are removed in the upper respiratory tract; but $PM_{2.5}$ can reach the alveolar region, which has no protective mucus layer. Industrialised countries such as the US have moved to regulate $PM_{2.5.}$ Efforts to measure the health effect of $PM_{2.5}$ in China were made for the first time in Chongqing (Xu and Johnson, 1997). Samples collected at five monitoring sites in Chongqing showed strong correlation between $PM_{2.5}$ and PM_{10}, with a $PM_{2.5}$–PM_{10} ratio of 0.77, compared with 0.60 in the US (US Environmental Protection Agency, 1982). If we use $PM_{2.5}$ to measure the health impact of sulphate concentrations in Shijiazhuang, we see considerably stronger health effects than for PM_{10} (Table 2, col. 1). The health cost increases from 4.3 per cent of GDP to 5.6 per cent of GDP in 2000.

The results in Table 1 are also sensitive to changes in valuation parameters. While the willingness-to-pay method used in Table 1 may be a preferred approach to valuing health damage, there is a concern for the accuracy of the willingness-to-pay survey in China where the markets for risk are still in infancy. One way attempted by the World Bank (1997) to provide internationally comparable estimates is to convert US estimates for a statistical life through comparing wage rates for risky and non-risky occupations and from contingent studies that estimate the value of making small reductions in the probability of death. Another option is to use the human capital approach to value health cost simply as lost productivity (discounted lost wage) and the costs of illness, which is a convenient way to estimate a complicated phenomenon as both wages and medical bills are easily observed.

These two alternative valuations are pre-

Table 1. Health effects of sulphate pollution above the national ambient standard: urban areas in Shijiazhuang, 2000

	Dose-response coefficients[a]	Health impacts	Economic valuation	
			Per unit ($)	In total ($ million)
Mortality				
Premature deaths	6	251	160 000	40.15
Morbidity (cases)				
Acute				
Respiratory hospital admissions	12	502	284	0.14
Emergency room visits	235	9 829	23	0.23
Lower respiratory infection/child asthma	23	962	13	0.01
Asthma attacks	2 608	109 076	4	0.44
Respiratory symptoms (thousand cases)	183	7 654	0.6	4.59
Chronic				
Chronic bronchitis	61	2 551	8 000	20.41
Restricted activity days (person/year)	157.5	6 589	846.8	5.58
Health cost in total ($ million)				71.5
Health cost as percentage of local GDP[b]				4.3

[a] Effects per 1 million people for every 1 mg/m^3 increase in ambient concentrations of PM_{10} (World Bank, 1997, p. 24).

[b] Derived from per capita GDP. Total GDP for Shijiazhuang municipality in year 2000 was RMB 100.1 billion and urban residents were about 14 per cent of the municipal population. The exchange rate was 8.34 RMB/US$ for year 2000.

Table 2. Sensitivity analysis of air pollution health effects in Shijiazhuang, 2000

	Higher impact in dose-response functions[a] (cases)	Lower value per statistical life ($ per case)	Alternative valuation by human capital approach ($ per case)
Mortality	8	60 000	8 970
Morbidity	241 479	1 387	253
Health cost in total ($ million)	92.9	39.3	21.2
Health cost as percentage of local GDP	5.6	2.4	1.3

[a] Effects per 1 million people for every 1 mg/m^3 increase in ambient concentrations of $PM_{2.5}$, converted from the PM_{10} dose-response functions using a $PM_{2.5}/PM_{10}$ ratio of 0.77 (Xu and Johnson, 1997).

sented in Table 2. Lowering the value of a statistical life from US$160 000 to the World Bank (1997) estimate of US$60 000 reduces the health damage estimate dramatically, by almost two percentage points of GDP. The results of the human capital approach appear implausibly low as the estimated health cost of 1.3 per cent GDP is even less than Shijiazhuang's current investment in environmental protection, which is about 2 per cent of local GDP (Shijiazhuang Municipal EPB, 2001).

6. Assessment of Control Options

Emissions of major air pollutants in Shijiazhuang have been falling in recent years under the Total Emission Control Plan enforced top–down from the central government by assigning emission quotas to local administrative areas.[7] However, efforts in emission reduction have not been matched equally by improvement in urban air quality from a human health perspective. The Shijiazhuang municipality has cut emissions well below its quota in recent years and SO_2 emissions declined by almost 30 per cent between 1998 and 2000; yet monitored ambient concentrations of SO_2 in Shijiazhuang dropped only slightly, from 116 to 112 (Shijiazhuang Municipal EPB, 2001). The fine particulate matter of sulphate was not monitored, but would be no better-off as SO_2 is the precursor to sulphate.

One reason for the discrepancy between emission reduction and air quality improvement is that emission control has been targeting the reduction of emission amount rather than the alleviation of environmental impact. Large point sources such as power plants account for the bulk of Shijiazhuang's total emissions, but contribute far less to ground-level concentrations due to elevated emission height. Cutting emissions from large power plants may help reaching an emission reduction target, but may not be effective in reducing ambient concentrations which are harmful to human health.

Several emission-control options for Shijiazhuang are compared here in terms of their effectiveness in reducing population exposure.

(1) A centrepiece of Shijiazhuang's plan is to substitute natural gas for coal, by tapping a pipeline being built to transmit natural gas from Shaanxi to Beijing. Shijiazhuang currently produces gas by coal gasification, which contributes only 2 per cent to the city's total primary energy use. The new access to natural gas will reduce Shijiazhuang's heavy reliance on coal by about 10 per cent and gasify residential and commercial applications and some industrial production within the second ring road of the city where the value of natural gas is highest in replacing coal to reduce the impact on human health.

(2) The overwhelming source of particulate concentrations in Shijiazhuang is from small area sources. A drastic measure adopted by Shijiazhuang has been to shut down small boilers and replace them with larger and more efficient facilities that reduce both energy consumption and emission. This has taken place mainly in the space heating sector. In recent years, over 700 small boilers used for winter heating have been demolished and replaced by central heating plants. The coverage of central heating now reaches half of the city area.

(3) The average sulphur content of the coal currently consumed in Shijiazhuang is about 1.5 per cent, which is half a percentage point higher than the generally acceptable sulphur level. A mandate to restrict the sulphur content to be 1 per cent for all coal sold and used in Shijiazhuang became effective in November 1999. Despite Shijiazhuang's proximity to Shanxi where low-sulphur coal is produced, the initiative has so far met with limited success. Coal sample tests done by the Shijiazhuang Municipal EPB in 2000 indicated that only about half of the coal used in the city was under the 1 per cent sulphur content limit.

(4) Technical options of desulphurisation have been actively explored by Shijiazhuang. Some technologies such as limestone injection and circulating fluidised bed are, how-

ever, costly. A widely adopted and less costly measure is to install wet electrostatic precipitators on boilers to remove both fine particles and sulphur from flue gas. By adding lime to the water used in the precipitators, the efficiency in removing sulphur increases from 10 per cent to 30 per cent for large boilers producing 10 ~ 70 tons of steam per hour (t/h) and to 50 per cent for small boilers of 1 ~ 10 t/h steam.

In addition, Shijiazhuang has also introduced pro-environment policy initiatives to enhance air quality management. These include the pollution levy, industrial structural adjustment and financial incentives for energy-efficiency investment. These initiatives provided policy support to air pollution control. The pollution levy programme, for example, charges non-compliance fees on air pollution violations. For SO_2 emissions, a fee of 200 RMB per ton applies to all SO_2 emitted without a threshold to discourage emissions. The effects of these initiatives are, however, difficult to quantify.

Table 3 presents the results of the effectiveness assessment for the four options outlined, using year 2000 as the baseline. Estimates of SO_2 emission reductions and the associated costs are obtained from the Shijiazhuang Municipal EPB, assuming all options are implemented fully as planned. Results of human exposure are generated by the UrBAT model, measuring the reductions in population exposure to above-threshold sulphate concentrations by million residents.

Among the four policies, low-sulphur coal ranks the highest in terms of both total reductions in emission and total reduction in population exposure (first and third columns). The differences among policies are somewhat greater in terms of exposure than emissions: for example, low-sulphur coal reduces emissions by 46 per cent more than does natural gas, whereas it reduces exposure by 56 per cent more. The differences among policies are especially striking when evaluated per unit cost (last two columns). Substituting natural gas for coal is reasonably effective but quite expensive, so that its effectiveness per dollar spent is barely one-third that of low-sulphur coal.

Given the overwhelming share of coal in energy consumption in Shijiazhuang, the potential to reduce pollution by using low-sulphur coal is enormous. This is attractive because Shijiazhuang is only likely to reduce its dependence on coal gradually. The 1 per cent sulphur content limit is, however, difficult to monitor and implement. A major barrier to the enforcement of this measure is the lack of economic incentives to use low-sulphur coal, which costs 20 ~ 30 RMB more per ton than the average coal. Coal price reform to reflect the environmental cost of sulphur content is the key to support the low-sulphur coal initiative and increase the use of cleaner coal in Shijiazhuang.

Market-based policy support is also important for the natural gas and central heating options, which are comparable to each other in their cost effectiveness. Sulphur dioxide and sulphate originating from the numerous coal boilers within the second ring road are the main source of pollutants associated with health problems. Without internalising the health cost through the polluter-pays principle, natural gas and central heating services will not be competitive with coal-based alternatives such as small coal boilers. Emission levy is potentially an important regulatory instrument to provide policy support. Shijiazhuang currently charges 200 RMB per ton of SO_2. The rate is low compared with 1200 RMB per ton charged in other cities such as Beijing and Guangzhou. Polluters in Shijiazhuang often opt to pay the levy rather than to take action on emission reduction, as the levy is lower than the potential emission abatement cost. This is particularly so for the technical measure of boiler desulphurisation, which appears to be a costly option.

7. Conclusions and Policy Implications

This paper uses energy emission data collected in Shijiazhuang to assess the environmental health effects of urban air pollution. Using an atmospheric dispersion modelling approach, an urban-scale spatial model is

Table 3. Effectiveness of air pollution control options for Shijiazhuang, 2000

	Reduction in sulphur emission (Kt)	Net annual cost[a] ($ million)	Decrease in human exposure (µg/m^3 by million population)	Effectiveness by sulphur emission (Kt/$ million)	Effectiveness by human exposure (µg/m^3 by population per $)
Natural gas	13	43	41	0.3	0.9
Central heating	3	12	10	0.3	0.8
Low-sulphur coal	19	27	64	0.7	2.4
Boiler desulphurisation	1	18	2	0.1	0.1

[a] The original Chinese estimates are converted to US$ using the year 2000 official exchange rate of 8.28 RMB/US$.

developed to identify the sources of emissions in Shijiazhuang and to estimate population exposure to high ambient concentrations of sulphate, a fine particulate matter that is most damaging to human health among air pollutants. Dose-response functions are used to quantify the impact on human health. The results show that the costs of premature deaths and morbidity cases amount to more than 4 per cent of GDP in Shijiazhuang for the year 2000, highlighting the significant health costs associated with air pollution in Chinese cities.

Comparison of the air pollution control options for Shijiazhuang shows a noticeable difference in the magnitude of cost-effectiveness between reducing emissions and reducing population exposure. The policy implication is significant. Emission reduction will benefit urban residents more if actions are focused on the alleviation of environmental impact instead of the reduction of total emissions.

Low-sulphur coal appears to be the most cost-effective option to reduce ambient concentrations of sulphate in Shijiazhuang. Market-based policy initiatives, such as coal price reform and emission levy, to internalise adequately the externality of the health costs associated with air pollutants are critical to support urban air quality management and improve population health.

Notes

1. China adopts three classes of ambient air quality standards. Class I are tourist, historic and conservation areas. Class II are residential urban and rural areas. Class III are industrial areas and heavy traffic areas. Chinese ambient air quality standards are comparable with those of the World Health Organisation (WHO, 2000). For example, the Chinese standards for annual concentrations of sulphur dioxide are 20 and 60 micrograms per cubic metre ($\mu g/m^3$) for Class I and Class II areas respectively. The WHO guidelines for threshold values of annual average sulphur dioxide concentrations to protect public health are $40 \sim 60\ \mu g/m^3$. For a detailed comparison, see World Bank (1997, Table 1.1).
2. In 1998, PM_{10} concentration violations were 50 per cent and 40 per cent higher in the degree of non-compliance than TSP violations in Tangshan (north China) and Guangzhou (south China) respectively. NO_x from vehicle emissions contributes increasingly to urban air pollution but mainly in very large cities where the average NO_x level was 57 $\mu g/m^3$ in 1998 compared to the standard of 50 $\mu g/m^3$. Lead (Pb) pollution has been dramatically reduced following the national ban on the production and sale of leaded gasoline on 1 July 2000. Carbon monoxide (CO) and ozone (O^3) are not systematically monitored (World Bank, 2001).
3. The five air quality monitoring stations use automated monitoring equipment. Data are transferred to the computer centre in the Shijiazhuang Municipal Environmental Protection Bureau from the following locations: Hebei Chemical Industry School, lat. 38° 5′, long. 114° 55′; Military Mechanic Institute, lat. 38° 06′, long. 114° 48′; No. 54 Institute (electrical equipuipment manufactory), lat. 38° 04′, long. 114° 44′; Pingan Power Station, lat. 38° 03′, long. 114° 49′; Development Zone, lat. 38° 00′, long. 114° 58′.
4. These figures exclude processed fuels, such as petrol and diesel, which are not considered in this study because the primary pollutants associated with them (mainly NO_x) are currently within the ambient standard.
5. Xu *et al.* (1994) used a Poisson linear method to regress daily mortality and morbidity against the logarithm of TSP and SO_2 in Beijing and found that the risks of chronic obstructive pulmonary disease increase by 38 per cent and 29 per cent with a doubling in TSP and SO_2 concentrations respectively and that the risks of total mortality increase by 11 per cent with a doubling in SO_2 concentrations. In other studies focused on TSP in Beijing (X. Xu *et al.*, 1995; Xu and Wang, 1993), a 100 $\mu g/m^3$ increase in TSP concentrations is associated with 1.1 per cent more hospital outpatients and 0.6 per cent more emergency room visits. Similar studies conducted in other Chinese cities such as Shanghai (Chen, 1994), Shenyang (Z. Xu *et al.*, 2000), and Chongqing (World Bank, 1996) all find significant correlation between ambient concentrations and respiratory diseases and premature mortality.
6. Converted from the Chinese currency *renminbi* (RMB) using the 1998 exchange rate of 8.28 RMB/US$. The survey was conducted in RMB. Annual wages in 1998 were RMB 7479 for China on average and RMB 6433 for Chongqing, equivalent to US$903 and US$777 respectively.

7. The State Environmental Protection Administration first introduced the Total Emission Control Plan in 1996 to control the total national emissions of 12 major air pollutants. Quotas were allocated to each of the 31 provinces and autonomous regions (including municipalities that report directly to the central government) to meet the national targets. The annual SO_2 emission quota for the Shijiazhuang municipal administrative area as a whole was 197 kilotons based on its 1995 emission level, which was set as the ceiling for annual emissions in the Ninth Five-Year-Plan (1996–2000). The quota was not met in the first 3 years and emissions peaked in 1998 at 218 kilotons, they have since come down to 154 kilotons in 2000 (Shijiazhuang Municipal EPB, 2001).

References

ARNDT, R., CARMICHAEL, G. and ROORDA, J. (1998) Seasonal source-receptor relationships in Asia, *Atmospheric Environment,* 32, pp. 1397–1406.

CALORI, G. and CARMICHAEL, G. (1999) An urban trajectory model for sulfur in Asian megacities: model concepts and preliminary application, *Atmospheric Environment*, 33, pp. 3109–3117.

CHEN, X. L. (1994) Study of health effects of low levels of sulphur dioxide (chronic respiratory diseases) in Shanghai, *Chinese Journal of Chronic Disease Prevention and Control*, 2, pp. 259–261.

DOCKERY, D. W., POPE III, C. A., XU, X. P. *ET AL.* (1993) An association between air pollution and mortality in six U.S. cities, *The New England Journal of Medicine*, 329(25), pp. 1753–1759.

FLORIG, H. (1997) China's air pollution risks, *Environmental Science and Technology*, 31(6): pp. 274A–279A.

FOELL, W., AMANN, M., CARMICHAEL, G. *ET AL.* (1995) *RAINS-Asia: an assessment model for air pollution in Asia.* Report on the World Bank Sponsored Project "Acid Rain and Emission Reduction in Asia", World Bank, Washington, DC.

HEFFTER, J. L. (1983) *Branching atmospheric trajectory (BAT) model.* Technical memorandum of the National Oceanic and Atmospheric Administration, ERLARL-121.

IIASA (INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS) (2001) *User instruction and manual for RAINS-ASIA version 7.52*. ASA, Laxenburg.

KALNAY, E., KANAMITSU, M., KISTLER, R. *ET AL.* (1996) The NCEP/NCAR 40-year reanalysis project, *Bulletin of American Meteorological Society*, 77(3), pp. 437–471.

LI, J., SCHWARRTZ, J. and XU, X. (1998) *Health benefits of air pollution control in Shenyang, China*. Research report, School of Public Health, Harvard University.

LI, Y., REN, Q. and NIU, X. (1998) *Benefit/cost analysis of environmental protection input and pollution damage in Shijiazhuang*. Shijiazhuang Environmental Protection Bureau, Shijiazhuang (in Chinese).

OAK RIDGE NATIONAL LABORATORY (2001) *LandScan 2000: Global Ambient Population, 2000.* (available at: http://sedac.ciesin.org/plue/gpw/landscan/main.html).

OSTRO, B. (1996) *A methodology for estimating air pollution health effects.* Technical Report WHO/EHG/96.5, World Health Organisation, Geneva.

SEPA (STATE ENVIRONMENTAL PROTECTION ADMINISTRATION) (2001) *Report on the state of the environment in China—2000, section on atmospheric environment.* State Environmental Protection Administration, Beijing (available at: http://www.zhb.gov.cn/bulletin/soe2000/english/atmospheric/atmospheric_e.htm).

SHAH, J. NAGPAL, T., JOHNSON, T. *ET AL.* (2000) Integrated assessment model for acid rain in Asia: policy implications and results of RAINS-Asia model, *Annual Review of Energy and Environment*, 25, pp. 339–375.

SHIJIAZHUANG MUNICIPAL ENVIRONMENTAL PROTECTION BUREAU (2001) *A background report on Shijiazhuang city prepared for the World Bank's China sulphur mitigation policy workshop in Beijing*. Shijiazhuang EPB, June (in Chinese).

STREETS, D., HEDAYAT, L., CARMICHAEL, G. *ET AL.* (1999) The potential for advanced technology to improve air quality and human health in Shanghai, *Environmental Management*, 23(3), pp. 279–295.

US ENVIRONMENTAL PROTECTION AGENCY (1982) *Air quality criteria for particulate matter and sulfur dioxide, Vol. I.* EPA-600/8-82-029A, USEPA, Research Triangle Park.

WHO (WORLD HEALTH ORGANISATION) (2000) *Guidelines for Air Quality*. World Health Organisation, Geneva. (available at: http://www.who.int/peh/air/Airqualitygd.htm).

WORLD BANK (1996) *China: Chongqing industrial pollution control and reform project*. Staff Appraisal Report, World Bank, Washington, DC.

WORLD BANK (1997) *China's Environment in the New Century: Clear Water, Blue Skies.* Washington, DC: The World Bank.

WORLD BANK (2001) *China: Air, Land, and Water, Environmental Priorities for a New Millennium*. Washington, DC: The World Bank.

XU, X. and JOHNSON, T. (1997) *Air pollution and* *its health effects in Chongqing, China.* World Bank Report, World Bank, Washington, DC.

Xu, X. and Wang, L. (1993) Association of indoor and outdoor particulate level with chronic respiratory illness, *American Review of Respiratory Diseases*, 148, pp. 1516–1522.

Xu, X., Gao, J., Dockery, D. and Chen, Y. (1994) Air pollution and daily mortality in residential area of Beijing, China, *Archives of Environmental Health*, 49(4), pp. 216–222.

Xu, X., Li, B. and Huang, H. (1995) Air pollution and unscheduled hospital outpatient and emergency room visits, *Environmental Health Perspectives*, 103(3), pp. 286–289.

Xu Z., Yu, D., Jing, L. and Xu, X. (2000) Air pollution and daily mortality in Shenyang, China, *Archives of Environmental Health*, 55(2), pp. 115–120.