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Air quality estimates in Taiyuan, Shanxi Province, China

Application of a multiple-source dispersion model

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Sammendrag: I en tidligere kostnads-fordels analyse av lokal luft kvalitets forbedringer i Shanxi er en enkel lineær modell for sammenhengen mellom utslipp og bakke konsentrasjoner brukt (Aunan et al, 2004). Dette prosjektet ser nærmere på sammenhengen mellom utslipp og bakkekonsentrasjoner, og en sprednings modell er tatt i bruk for å beregne luft kvaliteten i Taiyuan. Utslippskildene spenner fra stor industri til små husholdnings utslipp. Vi viser at selv med begrenset tilgang på data var det mulig å estimere luft kvaliteten temmelig nøyaktig. Vi brukte modellen på fem luftforbedrings prosjekter. De fem prosjektene inneholdt alt fra utslippsreduksjon i husholdningene til utslippsreduksjoner fra store skorsteiner. Vi viser at prosjekter som baserer seg på reduksjon i husholdningsutslipp eller små industri ofte er de mest effektive med tanke på å forbedre den lokale luftkvaliteten. Dette er fordi disse utslippene gjerne er i lav høyde og i umiddelbar nærhet av befolkningen. Utslippsreduksjoner fra høye skorsteiner er ofte så fortynnet før det når bakkenivå, at selv om reduksjonen er stor så har det relativt lite å si for partikkel eller SO2 konsentrasjonen i byen.

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Abstract: In a previous cost-benefit analysis of local air quality improvements in Shanxi, a simple linear relationship between emissions and surface concentrations was assumed (Aunan et al., 2004). This study looks more closely at the relationship between emissions and concentrations and employs a dispersion model to estimate the local air quality in Taiyuan based on the emissions from a variety of sources from large industry to households. We show that even with limited data availability we were able to make fairly accurate estimates of the air quality. We utilized the model on five abatement projects ranging from emission reductions in the households to tall industrial stacks. We show that the measures targeted at smaller industries and household consumption are often the most effective in terms of improving local air quality because these sources have low emission heights and are located in the immediate vicinity of the population. The larger industrial sources, though potent in the emission reduction, often have such tall stacks that the emissions are fairly diluted before they reach the ground and therefore have little effect on the concentration of particles or SO2 in the city.

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Contents

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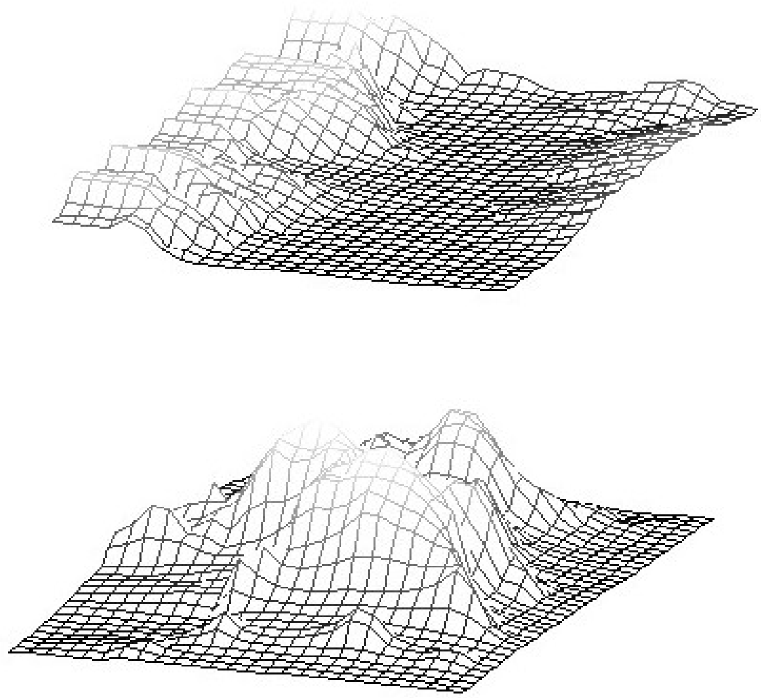

The top shows the topography of the modeling area, and the bottom the winter SO2 concentration.

1 Introduction

China is one of the fastest growing economies of the world, with an annual increase in GDP of 5.8% in the 1980s, 10.8% in the early 1990s (Gan, 1998) and 8-9% in the late 1990s (He et al., 2002). In the wake of economic growth follows increased energy consumption and urbanization. China has had a steady growth in primary energy consumption from the late 1970s to mid 1990s, but owing to a remarkable drop in energy intensity (Sinton et al., 1998) (i.e. consumed energy per production unit), the increase in primary energy consumption was limited, dropping in the late 1990s down to 1994 levels in 1999 (He et al., 2002). Even though the energy intensity has shown a dramatic decline, the energy consumption in China is still characterized by low efficiency and high emissions. The main energy carrier in China is coal, and from the late 1970s to the mid 1990s the increased primary energy consumption was largely provided by increased coal consumption. Coal stood for about 74% of primary energy consumption. The drop in primary energy consumption in the mid 1990s was due to a decrease in coal consumption (BP, 2003). Other sources were still rising. Since 1999 the primary energy consumption has been rising again, largely due to a new increase in coal consumption. The share of coal consumption of the primary energy in 2002 was 66.5%. With limited use of cleaning technologies and low energy efficiency, this places a heavy burden on the local environment, particularly in urban industrial areas. Coal consumption is also known to have severe negative effects on regional (acid rain) and global (greenhouse gas (GHG)) scales.

Taiyuan is generally recognized as one of the most polluted cities in the world. That it is built on heavy polluting industry and situated in Shanxi, the main coal province of China, contribute to this "status". The pollution problems are so severe that it was ranked the most polluted city in China in China's State of the Environment report (SEPA, 2000). In 1999 Taiyuan was elected the first cleaner production demonstration city in China. The goal is to improve the production at all stages and thus improve the environment as opposed to earlier efforts that focused on end of pipe improvements.

This new way of addressing pollution problems opens up for the possibility of co-benefits in that both the local and the global environment can benefit from the projects. Thus third parties like Norway can take an interest in the projects through the Clean Development Mechanism (CDM) of the Kyoto Protocol, opening for international funding in developing countries to reduce GHG emissions. In order to qualify for such funding the projects must contribute to sustainability. For these reasons, emphasizing co-benefits is essential.

This report is part of a larger project investigating the co-benefits of proposed abatement projects in Taiyuan (Mestl et al., 2004). In the larger project the potential for CO_2 reduction and health benefits of particulate emission reductions with possibilities for foreign CDM funding was investigated. The gaussian plume model AERMOD was used to estimate the spatial changes in the PM_{10} concentrations in the city due to the abatement projects.

In this report, the use of AERMOD for modeling the concentration changes in (Mestl et al., 2004) is described in more detail. In addition, the local air quality of Taiyuan is studied more closely and compared to locally reported monitoring of the air quality. Comprehensive data retrieval was undertaken, and 79% of all the industries and the households are included in an estimate of the total air quality status of the city, using this model.

The report proceeds as following: The model is presented in chapter 2, and the environmental status of Taiyuan is discussed in chapter 3. In chapter 4, the data presented in chapter 3 is used in the model to estimate the air quality of the city. Cleaner development projects are presented and studied in chapters 5 and 6, and the model sensitivity is checked in chapter 7.

2 The model

AERMOD is a model developed by the US Environmental Protection Agency (EPA) in conjunction with the American Meteorological Society (AMS) (US-EPA, 1998b). The model can estimate the emission dispersion from multiple sources for varying terrain and meteorological conditions differentiating between urban and rural environment. The sources can be point sources, area sources and volume sources. Concentration values can be calculated for points at ground level or any chosen elevated position. It is also possible to obtain concentrations at different elevations for a single grid point.

AERMOD was primarily made for estimates in the US and other Western countries where the data availability is good. Very detailed data on emissions, meteorology and terrain are therefore input to the model.

Emissions

The modeled air quality is obviously directly dependent on the emissions. The dispersion modeling requires the following data: emission rate, height and position, and whether or not the source is in an urban area. For the point sources stack diameter, exit velocity and temperature are also required.

Meteorology

The model uses hourly measurements of temperature, wind direction and speed, and cloud cover. In addition the model needs upper air morning soundings (i.e. weather balloon measurements). Wind speed and direction, temperature, pressure and humidity are measured at increasing altitudes.

The model also needs some constants for estimation of the boundary layer conditions. These are albedo, Bowen ratio and surface roughness length.

The albedo is the fraction of total incident solar radiation reflected by the surface back to space without absorption. Typical values range from 0.1 for thick deciduous forests to 0.90 for fresh snow. The albedo varies during the day with its lowest value at noon, and the highest in the night. The noontime albedo is input to the program. The hourly variation is then calculated based on this, and with the albedo set to 1.0 in the night.

The daytime Bowen ratio, an indicator of surface moisture, is the ratio of the sensible heat flux to the latent heat flux and is used for determining planetary boundary layer parameters for convective conditions. While the diurnal variation of the Bowen ratio may be significant, the Bowen ratio usually attains a fairly constant value during the day. Midday values of the Bowen ratio range from 0.1 over water to 10.0 over desert.

The surface roughness length is related to the height of obstacles to the wind flow and is, in principle, the height at which the mean horizontal wind speed is zero. Values range from less than 0.001 m over a calm water surface to 1 m or more over a forest or urban area.

Terrain data

AERMOD has the capacity to include terrain in the calculations. Terrain data is included at each grid point as height above sea level, and a height scale at that grid point representing the hilliness of the landscape.

3 Environmental status of Taiyuan

Taiyuan is a city built on heavy industry with a population of 3.0875 million in 2000. The total area of Taiyuan is 6988 km2, which includes six districts, three suburban counties and one satellite city. The urban area of Taiyuan is 1460 km2, and includes the six districts, with a population of 2.332 million and built-up area of 195 km2. Our investigation is limited to covering the urban area.

Taiyuan lies in the province Shanxi, China's main coal province. Thus the natural energy source is coal. This leads to large SO_2 and particle emissions.

The air quality of Taiyuan is monitored from five monitoring stations as shown in Figure 3.1. At these stations the concentration of Total Suspended Particles (TSP), SO_2, NO_x, and CO are monitored.

Table 3.1 shows the annual average concentration in $\mu g/m^3$ of TSP and SO_2 as reported in (EQRT, 2000). We see that there is a trend of improved air quality in terms of the TSP concentration. This is probably a result of investments in cleaner technology in the industries, and increasing use of district heating and coal gas in the households in resent years. The same trend is not seen in the SO_2 concentration, and is probably because the increased use of cleaner technology focuses on particle emissions and not SO_2.

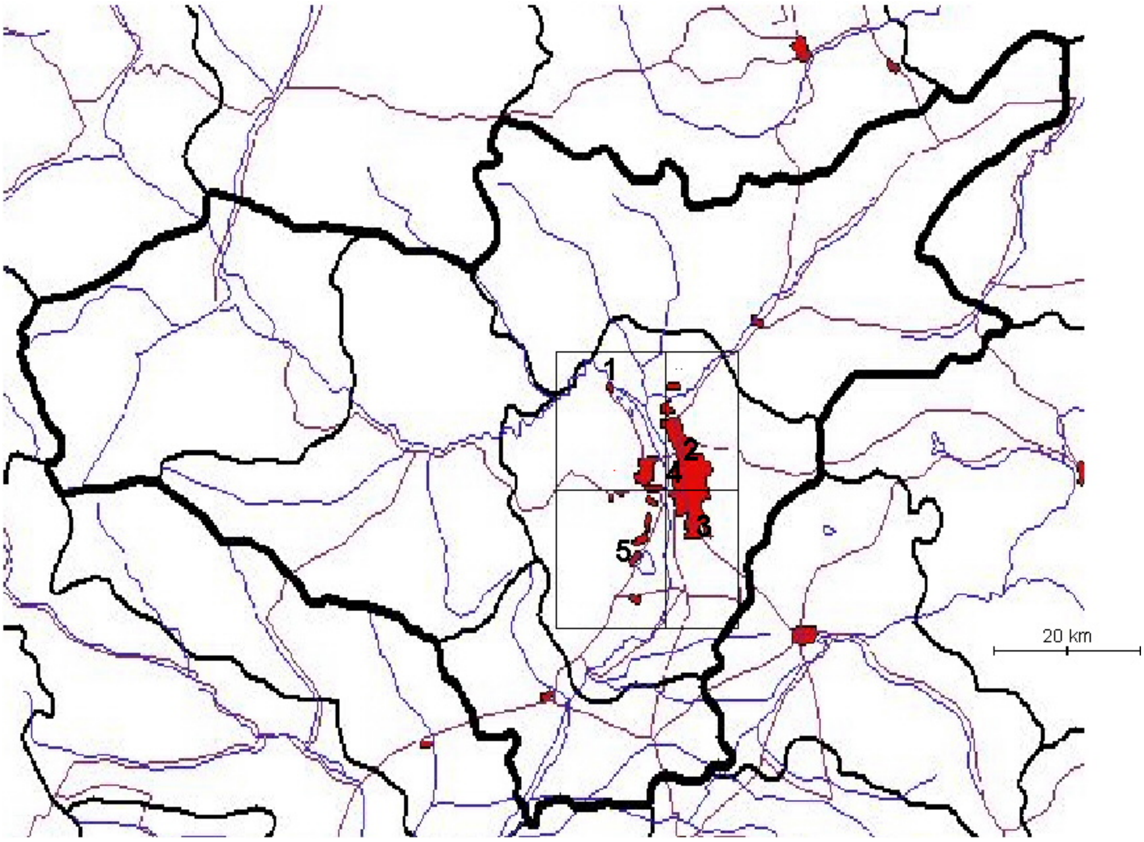

Figure 3.1 Map of Taiyuan city. The area within the thick line comprises the six districts, three suburban counties and one satellite city of Taiyuan. The rectangle indicates the modeled area, and covers most of the six districts. The areas of the city with an urban character (called the built-up area or construction area) are shown in gray. Numbers 1-5 represent the five monitoring stations where regular measurements of TSP, SO2, NOx, and CO are made.

Table 3.1 Reported concentrations in μg/m3 of Total Suspended Particles (TSP) and SO2 in Taiyuan in the years 1996-2000.

	Year	**Monitoring station number** 1	2	3	4	5
TSP	1996	417	602	476	490	491
	1997	432	622	462	467	466
	1998	411	593	460	476	463
	1999	469	492	379	446	347
	2000	353	431	378	402	394
SO_2	1996	245	196	246	192	190
	1997	157	260	224	201	308
	1998	121	296	267	281	268
	1999	212	291	313	275	209
	2000	199	231	206	184	177

Terrain

Shanxi is a mountainous province with a valley stretching north south. Taiyuan lies in this valley, and is surrounded by mountains to the west and east. The valley narrows at the north end of Taiyuan and is wide and open to the south.

Meteorology

Taiyuan has a dry inland climate dominated by low wind speeds. The dominating wind directions are along the valley from southeast or north/northwest, with the stronger winds from the north, indicating a quicker dispersion.

Two years of hourly measurements of wind speed and direction, temperature and cloud cover were downloaded from (WeatherOnline, 2002). The year November 2000 to November 2001 was used in the base runs, and the following year, November 2001 to November 2002, was used for comparison.

Lying in a basin and with low wind speeds, Taiyuan has very frequent inversion both in summer and winter. Inversions lay a lid over the area, preventing the pollutants from escaping, and deteriorating the air quality. On average there is inversion 80% of the time with a height of about 500 m in winter, whereas in summer the frequency is 60% and average height 250 m.

Upper air soundings for the Taiyuan area were not possible to retrieve, and thus they were constructed based on the average conditions with frequent inversion as described above. The inversion is modeled as a temperature inversion in the upper air soundings at the right levels. The sensitivity to this obvious lack of data is tested in chapter 7.

The constants for albedo, Bowen ratio and surface roughness length were chosen from lookup tables in ((US-EPA, 1998a) as given in

Table 3.2. Taiyuan is assumed to have average moist to dry conditions for the choice of the Bowen ratio. The city is chosen as urban/grassland for the roughness length, and urban for the albedo. The sensitivity to these constants is tested and discussed in chapter 7.

Table 3.2 Meteorological constants used in the model

	Winter	Summer
Albedo a_0	0.35	0.16
Roughness length r_0 (m)	0.5	0.5
Bowen ratio B_0	2.0	2.0

3.1 Emissions

To model the air quality, a detailed emissions inventory is needed. In this report only stationary sources are included, and of them only the sources using coal. In 1998, 99% of the stationary energy consumption was coal, whereof 5% was indirect as coal gas in the households (Taiyuan Government, 2001). The energy consumption in the transport sector is only 0.4% of the stationary, so its contribution to total emissions is negligible. However, these are generally low-level emissions and may contribute significantly to the air quality around large streets. This point has been left for later research.

The stationary energy consumption can be divided in three sectors: industrial, commercial and domestic.

The domestic sector includes all emissions from private homes, cooking, hot water and heating.

The commercial sector includes service companies like hotels and restaurants, schools, public organization and government.

The industrial sector includes all other production units from large power plants and metal smelting with several thousand workers to small one-man companies.

Emissions from the larger industries are routinely reported in environmental reports. Annual emissions of TSP and SO_2 are reported. The TSP emissions are divided in two types: either combustion related or production related (called "process emission").

All the sources are modeled as urban sources, i.e. they are located in an urban environment with a population of 2.3 million within the modeling area.

Combustive emissions

With Taiyuan being an industrial city, the main share of coal consumption and thus emissions comes from the industry. The industries stand for 76% of combustive TSP and 88% of SO_2 emissions (EQRT, 2000), (Aunan et al., 2004). For more detail see the appendix.

Of the reported industrial emissions, we were able to locate five industries emitting 52% of industrial TSP and 63% of industrial SO_2. The five industries are treated in more detail in section 3.1.1. The exact locations and conditions of the remaining industries are not known. They are treated as 'small industries' scattered around the city with low emission heights.

The households contribute 20% of the TSP emissions and 8% of SO_2 emissions. These emissions are associated with heating, and thus only occur in winter. The emissions are from low heights and scattered all over the city's living area.

The commercial sector consumes approximately half the coal of the households (Sinton and Fridley, 2000). We assume industrial emission factors for this consumption, and thus they contribute 4% of both TSP and SO_2 emissions in the city. The emission height is the same as for the scattered industries, and thus the commercial and scattered industrial emissions are treated together as 'small industries'.

The households and the 'small industries' are treated as area sources as described in section 3.1.2.

Process TSP

Process dust emissions reported in the environmental reports are of the same order of magnitude as the TSP emissions from combustion. The emission height of process dust is generally low, and therefore contributes substantially to the locally suspended dust. The main problem with modeling this contribution is that its origin is unclear (i.e. location, height and PM10 share).

Of the reported process dust emissions, the Iron & Steel Company stands for 46%. We include this in the modeling as described below. The remaining process dust is included in the modeling of 'small industries' as described in section 3.1.2.

3.1.1 Location and emission rates for the five large industries included in the model

The five industries included in the modeling are:

1. Taiyuan Cogeneration Power Plant No. 1
2. Taiyuan Cogeneration Power Plant No. 2

3. Taiyuan Iron & Steel Company
4. Xishan Coal and Power Group Company LTD.
5. Taiyuan Heavy Machinery Making Group Company LTD.

The first three are the largest industrial emitters in Taiyuan representing 50% of industrial TSP emissions and 60% of industrial SO2 emissions.

The dust emissions are reported as TSP, and not PM_{10}. The PM_{10} share is not exactly known, but on average for conventional combustion we assume the share to be 55%. In the 1990s there were efforts made in China to reduce the dust emissions from power production. This has led to the use of cleaning technology, e.g. Electric Static Precipitator (ESP), at the power plants. This technology is often efficient at cleaning large particles, and thus the PM_{10} share of the remaining dust increases (He et al., 2002). We assume the PM_{10} share at the two power plants and at the power-producing unit of the Iron & Steel Company to be 70%.

Table 3.3 shows the emission data used for the five industries included in the modeling. The location of the five industries is shown in Figure 3.2.

Table 3.3 Emission data from combustion for the five industries included in the modeling.

	Annual SO_2 emissions (t/a)	Annual TSP emissions (t/a)	Emission rate SO_2 ($g \cdot s^{-1} stack^{-1}$)	Emission rate PM_{10} ($g \cdot s^{-1} stack^{-1}$)[(a)]	# stacks[(b)]	Exit velocity ($m \cdot s^{-1} stack^{-1}$)	Exit tempera-ture (°C)	Exit diame-ter (m)
Taiyuan Cogeneration Power Plant No. 1	60624	12888	961	144 (70)	2 (210/230)	29	100	5
Taiyuan Cogeneration Power Plant No. 2	35583	10680	564	119 (70)	2 (180/210)	14	100	5
Taiyuan Iron & Steel Company	10517	3938	42	9 (55)	8 (30)	17	160	2
	5239	1969	24	5 (55)	7 (60)	19	160	2
	5239	1969	56	15 (70)	3 (100/120)	20	120	3
Xishan Coal and Power Group Company LTD.	6004	1441	190	33 (55)	1 (40)	24	160	3
Taiyuan Heavy Machinery Making Group Company LTD.	2194	232	70	25 (55)	1 (40)	5	160	3

[a] PM_{10} share (%) in parentheses

[b] Stack height (m) in parentheses

Taiyuan Iron & Steel Company

The Taiyuan Iron & Steel Company is the largest employer in Taiyuan with about 65,000 employees. The company produces 0.7 Mton of stainless steel per year, and to that end they produce 1.3 Mton of coke per year, and have a 76 MW power plant. The company is located in the northern part of Taiyuan city, within the residential/commercial areas. The reported number of stacks in this company is 54, but the exact data were not possible to retrieve. However we do know that the company has a power plant with three stacks that are 100–120 m tall and with an exit temperature 120 ^{0}C. Further, we know that there are several boilers on the premises with typical heights between 20 and 40 m and release temperatures around 160 0C. There are also several furnaces and other combusting units that have been modeled with stack heights at 60 m and a release temperature of 160 ^{0}C.

We do not know the share of TSP and SO_2 emitted from the different stack types, but as an estimate for the modeling we have used eight stacks at 30 m releasing 50%, seven stacks at 60 m releasing 25%, and the final 25% from the power-producing unit with two stacks at 120 m and one at 100 m. The stacks have been placed at random within the company area.

In addition there is a large amount of dust emitted during production at the Iron and Steel Company. According to an environmental report of the company there are 25 sources of dust at the premises. The origin and nature of these sources are not reported, but we were able to extract some information about emissions related to the steel production.

The annual reported process dust emissions at the Iron and Steel Company is 20 Mkg/a. Approximately half this dust comes from the steel production. The steel production uses heavily polluting electric stoves, and each stove generally has an inefficient bag house and a stack. The stacks are 20 m high, and emit approximately one-quarter of the dust emissions of steel production at a temperature of 160 ^{0}C. The remaining three-quarters of the emissions are reported as non-organized or diffuse emissions and take place within the factory hall at ground level. From tables we found that steel production is associated with a diffuse emission factor of 10–15 kg TSP/ton steel, i.e.7–10.5 Mkg TSP from a 0.7 Mton production.

For the modeling we assume that the remaining process dust is emitted in a similar manner, i.e. in total we model one-quarter of the process dust to come from 10 stacks at 20 m, and three-quarters of the process dust to be released in 10 factory halls with an emission height of 5 m and window/door area of 100 m^2. The stacks and area sources are spread over the company premises. The PM_{10} share of the process dust is said to lie between 55% and 80%. We use 70% in our modeling. The process dust emission is modeled as shown in Table 3.4 and Table 3.5.

Table 3.4 Process dust emissions from stacks comprising one-quarter of the process dust at the Iron and Steel Company.

	TSP emission (t/a)	**Emission rate PM_{10} ($g \cdot s^{-1} stack^{-1}$)**	**# stacks**	**Stack height (m)**	**Exit velocity ($m \cdot s^{-1} stack^{-1}$)**	**Exit tempera-ture (^oC)**	**Exit diameter (m)**
Taiyuan Iron & Steel Company, stack emissions	4921	10.92	10	20.0	10.0	160	2.5

Table 3.5 Process dust emissions from factory halls comprising three-quarters of the process dust at the Iron and Steel Company.

	TSP emission (t/a)	**Emission rate PM_{10} ($g \cdot s^{-1} m^{-2}$)**	**Total release area (m^2)**	**# factory halls**	**Release height (m)**
Taiyuan Iron & Steel Company, diffuse emissions	14764	0.33	1000	10	5.0

Xishan Coal and Power Group Company LTD and Taiyuan Heavy Machinery Making Group Company LTD:

Both companies have several boiler houses and up to 50 stacks. Exact data was not available. The industries have been simulated each with one stack of 40 m, temperature 160 ^{0}C and exit diameter 3 m. This is based on our own observations and consultations with staff members.

3.1.2 Household emissions and small industries

Household emissions

In Taiyuan there has been a large increase in the number of districts provided with district heating and supplied with town gas (coal gas) over the last years. There is now only a 10% share of the households still using raw coal or briquettes for cooking, primarily in the rural areas. In the urban areas the town gas coverage is 91% (Zhang K et al., 2003). In areas covered with both district heating and town gas, it is assumed that the need for individual coal combustion is eliminated, and we model these areas with no household emissions. Town gas combustion is relatively clean and emits very little compared to coal. In areas without district heating it is assumed that coal is used for heating in the winter.

The household coal consumption for the years 1995–1997 is taken from (Aunan et al., 2004) along with the typical emission factor for this kind of use. It is assumed that this coal consumption was reduced 10% by the year 2000 due to new areas with district heating and distribution of coal gas.

The household consumption is modeled as area sources with a release height of 12 m and a vertical distribution of 5 m. The areas cover 200 km^2 of the city living area. Household coal consumption is only in the heating season November–March. The emission data used for the modeling is shown in Table 3.6, and the areas are shown in Figure 3.2. The household consumption is the only one to be modeled with a seasonal varying consumption rate. The PM_{10} share is set to 55%.

Small industries

The category ‘small industries’ includes all industrial emissions not treated as point sources as discussed in section 3.1.1, and the commercial emissions. The PM_{10} share of both the combustive emissions and process dust is set to 55%.

The combustive emissions are from small boilers with stacks 20–40 m distributed all over the city. As with the household emissions they are modeled as scattered area sources at 30 m with a vertical distribution of 10 m. They cover 90 km2 of the city construction area.

The process dust is probably released closer to the ground, but to save computing time the emissions are modeled at 30 m along with the combustive emissions. The results would have been somewhat higher if the emissions had been modeled closer to the ground, but compared to other uncertainties in the modeling we feel confident that this timesaving error is tolerable.

The emission data are shown in Table 3.6.

Table 3.6 Emission and consumption data for the households and small industries in Taiyuan

	Coal con-sump-tion (Mt/a)	Release height (m)	Area (km^2)	SO_2 Emissions			TSP/PM_{10} (55%) emissions		
				Emission factor (kg/t)	(t/a)	($g{\cdot}s^{-1}m^{-2}$)	Emission factor (TSP) (kg/t)	TSP (t/a)	PM_{10} ($g{\cdot}s^{-1}m^{-2}$)
Small industries	3.67	30	90	18.1	66427	2.35E-05	8.0	29360	5.71E-06
Small industries, process dust included								52345	10.14E-06
Household (winter)	0.89	12	200	20.2	17889	6.89E-06	20.0	17712	3.75E-06

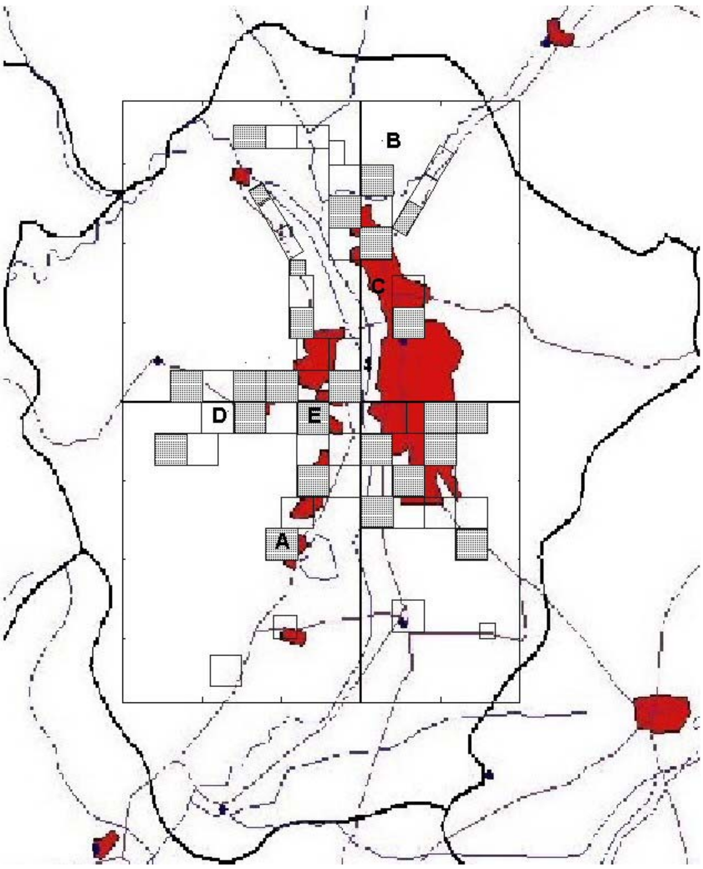

Figure 3.2 Source location. A: Taiyuan Cogeneration Power Plant No. 1, B: Taiyuan Cogeneration Power Plant No. 2, C: Taiyuan Iron & Steel Company, D: Xishan Coal and Power Group Company LTD, E: Taiyuan Heavy Machinery Making Group Company LTD. The boxes symbolize size and location of the area sources. All areas, the finely hatched and the transparent, represent the household sources. The finely hatched areas represent the small industries. The frame covers 950 km2, 38 km North-South and 25 km East-West.

4 Air quality modeling

The surface concentrations of PM10 were estimated using the data as described in Section 3. The air quality is averaged over the winter and summer seasons separately, and not over the year as is normally seen. This is done to visualize the seasonal varying household consumption rates. The results are shown in Figure 4.1.

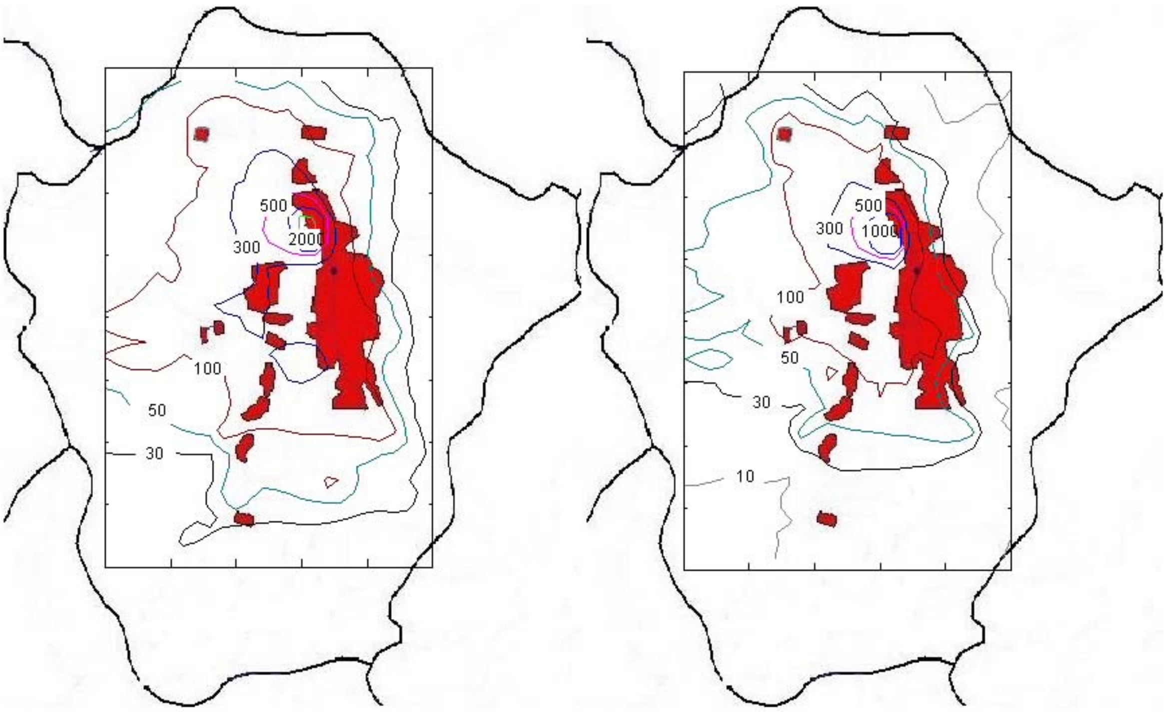

Figure 4.1 PM10 concentration in Taiyuan (µg/m3). Left: winter. Right: Summer. The modeling area covers 25 x 38 km.

The highest PM_{10} concentration is found in the vicinity of the Iron and Steel Company. This is not surprising since the company is one of the largest emitters in the city, with many low sources.

We also note that the power plants, the two largest emitters in the city, give no large contribution to the local air quality. They are located in the northeast and the southwest quadrants of the modeling area in Figure 4.1. We can see that there is no significant rise in the PM_{10} concentration around the power plants. This observation has to be ascribed to the fact that the power plant stacks are tall, and therefore the emissions are carried far and diluted before they reach the ground.

The concentration in winter is slightly higher than in summer, as would be expected since the household emissions are only in winter and from low heights.

TSP concentrations are measured routinely in Taiyuan, while only sporadic measurements of PM_{10} (i.e. particles with diameter less than 10 µm) have been performed. We therefore compare our results with the monitored annual TSP concentration. Our results are calculated for the year November 2000 to November 2001. These are then compared to the monitored

TSP concentrations of 2000, since that is the most resent measurement that we have. The figures are listed in Table 4.1

Table 4.1 Comparison of modeled PM10 concentration and measured TSP concentration at the five monitoring stations of Taiyuan. Background dust in Taiyuan is estimated to be 160µg/m3 and is subtracted from the monitored values before comparison to the estimated values.

	Monitoring station number (height(m))				
	1 (6)	**2 (9)**	**3 (8)**	**4 (10)**	**5 (10)**
Measured TSP concentration values from EQRT subtracted background dust of 160 (µg/m^3)	193	271	218	242	234
Estimated PM10 concentration	124	148	120	136	89
Estimated/ measured	0.64	0.55	0.55	0.56	0.38

The background dust arising from natural sources in the vicinity of the city is reported to be on an annual basis roughly 41% of total TSP (SSAAT, 2002), and 41% of the reported TSP is on average 160 µg/m3. We subtract that from the monitored data and compare to our estimated PM10 values (see Table 4.1). In our modeling we use PM10 fractions 0.7 and 0.55. Ideally, the fraction [estimated PM10/(monitored TSP- background)] should therefore lie between 0.7 and 0.55. The process dust of the industries, except at the Iron and Steel Company, is probably modeled too high above the ground, but on the other hand we do not know if a 55% PM10 fraction for process dust might be too high, balancing this error. Also there are sources not included in the modeling, both stationary and mobile. The overall contribution from traffic is probably small, as noted in section 3, and very local around the streets. However we do not know whether the monitoring stations lie close to large streets or not, and thus traffic might be important to the monitored values. Nevertheless we would expect the data errors to balance each other or tend to underestimate the concentrations. A fraction [estimated PM10/(monitored TSP- background)] around 0.5 therefore seems reasonable.

We also estimated the SO_2 concentrations in the city based on the same data. Figure 4.2 shows the concentrations in summer and winter. For SO_2 the distinction between summer and winter concentrations is much more evident. This is because the PM_{10} concentration is dominated by process dust at the Iron and Steel Company, which is so large that other variations tend to 'drown' as noise. This source does not emit SO_2, and other variations can be seen.

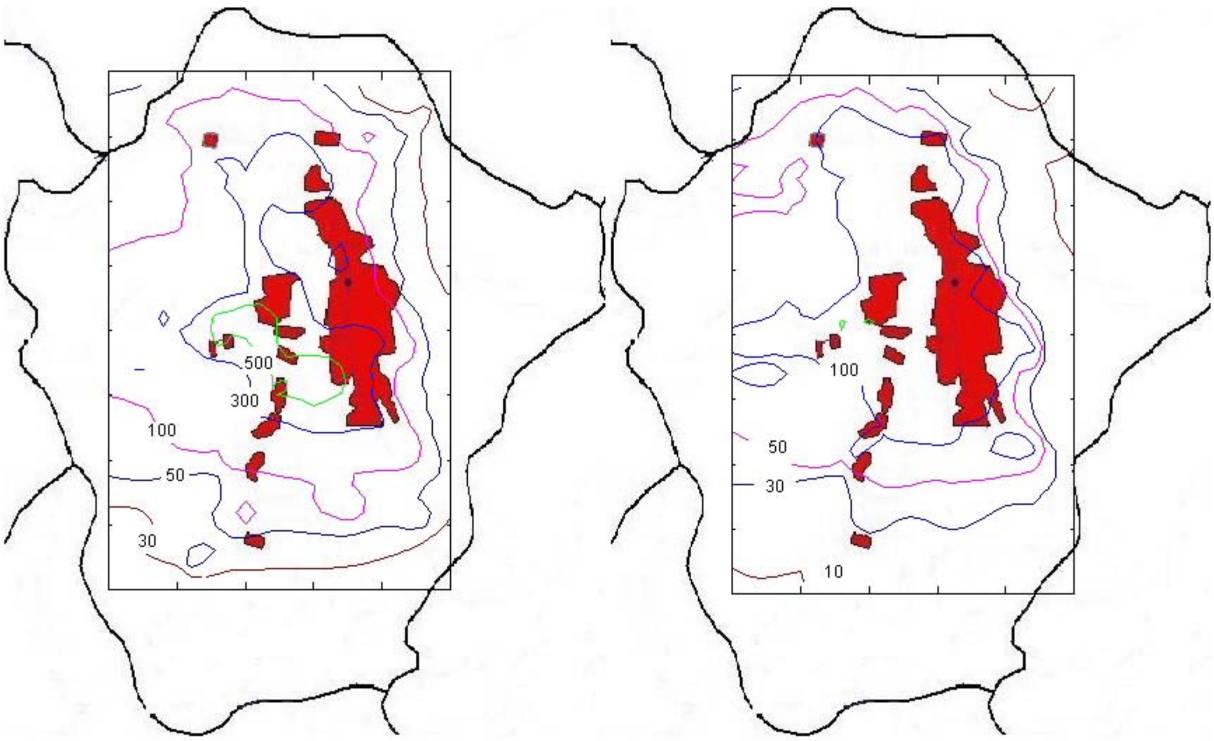

Figure 4.2 SO2 concentration in Taiyuan (μg/m3). Left: winter. Right: Summer. The modeling area covers 25 x 38 km.

The comparison between estimated and monitored concentrations is shown in Table 4.2

Table 4.2 Comparison of modeled and measured SO2 concentration in μg/m3 at the five monitoring stations of Taiyuan. Background level of SO2 in Taiyuan is estimated to be 28μg/m3 and is subtracted from the monitored values before comparison to the estimated values.

	Monitoring station number (height (m))				
	1 (6)	**2 (9)**	**3 (8)**	**4 (10)**	**5 (10)**
Monitored SO_2 concentration in year 2000 subtracted background level of 28 (μg/m^3)	171	203	178	156	149
Estimated SO_2 concentration (μg/m^3)	179	188	209	180	177
Estimated/monitored	1.05	0.92	1.17	1.15	1.19

The background level of SO_2 arising from long distance sources is estimated to be 28μg/m^3 (Aunan et al., 2004). From the table we see that there is good agreement between monitored and estimated SO_2 concentrations at all stations.

Altogether we think that considering the uncertainties in the input data, the modeling has given fairly accurate results for the air quality.

5 Clean Energy Projects

We analyzed six cleaner production projects in Taiyuan all included in the Clean Energy Action and Implementation Plan of Taiyuan, which lists cleaner production projects in the city. The projects were chosen with an eye to data abundance and data reliability. Reliable data were found for four energy efficiency projects at the Taiyuan Iron and Steel Company that recently have been negotiated with the Japanese International Cooperation Bank.

Some of the projects will reduce emissions both directly and indirectly. The direct emissions reductions are the on-site reductions accomplished through cleaner technology and coal savings. The indirect emissions reductions are a result of the projects leading to a reduced need for electricity from the municipal power plants. The indirect savings will thus reduce the demand for electricity from the coal-fired power plants and therefore reduce the emissions from these sources. There is no way of telling where the purchased electricity was produced, and therefore the indirect reductions are modeled as giving equal reductions at the two power plants. The projects are summarized in Table 5.1 and described in more detail below.

Table 5.1 Emission rates for the projects described.

Project	Direct TSP reduction (t/a)	Height (m)	Source type	Old PM_{10} emission rate[a)]	New PM_{10} emission rate[a)]	Indirect[b)] TSP reduction (t/a)	Change in PM_{10} emission rate ($g \cdot s^{-1} stack^{-1}$)
Project no. 1 CDQ	116	100/120	Stack	14.57	13.71	37	0.20
Project no. 2 EAF	1384	30		See Table 5.2 and Table 5.3		56	0.31
Project no. 3 CCPP	17.5	100/120	Stack	14.57	14.44	1095	6.08
Project no. 4 TRT	0		NA	0	0	96	0.53
Project no. 5 DBH[c)]	380	12	Area	3.75E-06	8.7E-08	0	0
	590	30	Area	5.69E-06	3.7E-08		
	220 (added)	120	Stack		8.57		
Project no. 6 CB	3200	30	Area	5.69E-06	5.07E-06	0	0

[a)]Stack emissions are in ($g \cdot s^{-1} stack^{-1}$) and area emissions are in ($g \cdot s^{-1} m^{-2}$)

[b)]Indirect emission changes are at the four municipal power plant stacks

[c)]380t/a and 590t/a are reductions from the households and small industries in the area. 220t/a is new emissions from the planned boiler house

5.1 Projects and background data at Taiyuan Iron and Steel

Project no. 1, Coke Dry Quenching (CDQ). Compressed nitrogen gas is used to quench coke from 1000 °C to 200 °C in a process of coke dry quenching (CDQ). At batteries nos 5 and 6 of the coking factory at Taiyuan Iron and Steel, 1.1 million tons of coke will be quenched this way. The heat from the nitrogen gas will then produce steam to run a 3000 kW electrical power generator through a waste heat recovery boiler. The project will produce electricity and save water. In addition to direct emission reductions the electricity will indirectly save coal and emissions at the municipal power plants. In total the project saves 153 tons of TSP and 340 tons of SO2 annually.

The project will reduce the TSP emissions with 116t/a from the on-site power plant reducing the PM_{10} emission rate of these three stacks at 100 and 120m from 14.57g·s^{-1}stack^{-1} to 13.71g·s^{-1}stack^{-1}. The indirect savings due to the reduced need of purchased electricity from the municipal power plants will be 37t/a TSP. The PM_{10} emission rate will thus be reduced with 0.20 g·s^{-1}stack^{-1} at each of the power plant stacks. This is the only project that we have been looking at that is currently under construction.

Project no 2, **Electrical Arc Furnace (EAF).** Six small energy-demanding and heavy-polluting electric stoves in the steel mill of Taiyuan Iron and Steel will be replaced with a big electrical arc-cast furnace giving a large direct emission reduction. This will also reduce electricity consumption by almost 20%, leading to indirect emission reductions. In total the project saves 1440 tons of TSP, most of which is direct emissions, and 283 tons of SO_2.

Each of the six existing stoves has an inefficient bag house and a stack. The stacks are 20 m high and have inner diameter of 2.5 m. The bag houses are able to receive only 60% of the emitted gas, and the cleaning capacity is 80%. The stack emissions from the stoves have been measured to 7.9kg/h TSP and release temperature 160 ^{0}C. The PM_{10} share is not known, but is reported to lie between 0.55 and 0.8. We use 0.7 in our estimates.

Within the factory hall there are emissions known as "diffuse emissions." From tables we found that steel production is associated with a diffuse emission factor of 10–15kg-TSP/ton-steel. The six existing stoves have a production capacity of 0.24 Mton of stainless steel per annum, i.e. 2.4–3.6 Mkg TSP. We adopt the lower limit. We assume that these emissions are within a factory hall with open doors and windows. The air exchange rate in the hall is assumed to be around one exchange per hour. At this rate we deduce that 65% of the PM_{10} eventually drifts outside and contributes to the outdoor air quality (Riley et al., 2002). The sensitivity to these assumptions is tested in section 7.2.

A new efficient furnace will replace the six stoves and will emit approximately 195.2t/a TSP. This replacement will eliminate the diffuse emissions and substitute the six existing stacks with one new taller stack. The direct emission reduction is stipulated to 1384t/a TSP. The emissions before and after the project is implemented are listed in tables 5.2 and 5.3.

Table 5.2 Diffuse emissions from steel mill producing 0.24 Mton/a of stainless steel at the Iron and Steel Company. These emissions will be eliminated if project no. 2 is implemented. PM_{10} share is 70%.

	Emission factor (kg-TSP/t-Steel)	**Steel production (t/a)**	**TSP emission in factory hall (kg/h)**	**Factory hall open window /door area (m^2)**	**Share of indoor PM_{10} penetrating outdoors**	**Emission rate PM_{10} ($g \cdot s^{-1} m^{-2}$)**	**Emission height (m)**
Emissions within factory hall	10	240,000	274	100.00	0.65	0.35	5.0

Table 5.3 Stack emissions from steel mill producing 0.24Mton/a of stainless steel at the Iron and Steel Company before and after project no. 2 is implemented. PM10 share is 70%.

Stack emissions	TSP emission (t/a)	Emission rate PM_{10} ($g \cdot s^{-1} stack^{-1}$)	#stacks	Stack height (m)	Exit temperature (K)	Stack diameter (m)	Exit velocity (m/s)
Before measure 2 is implemented	415.2	1.54	6	20	433	2.5	10.0
After measure 2 is implemented	195.2	4.33	1	60	433	4.5	21.0

The indirect emission reduction of TSP is 56t/a. The PM_{10} emission rate will thus be reduced with a 0.31 $g \cdot s^{-1} stack^{-1}$ at each of the power plant stacks.

Project no. 3, **Combined Cycle Power Production (CCPP).** The project enables combined cycle power production using blast furnace gas. The project consists of a gas turbine, a heat recovery boiler and a steam turbine. It will use 200,000 m^3/h of gas to produce electricity from an 83,000 KW power generator. In addition the project will produce steam in the heating season. The emission reduction is 1112 tons of TSP, and 5540 tons of SO_2. The major part of these savings is indirect due to reduced electricity consumption. The direct TSP emission reduction is only 17.5 t/a, reducing the PM_{10} emission rate from the on site power plant from 14.57 $g \cdot s^{-1} stack^{-1}$ to 14.44 $g \cdot s^{-1} stack^{-1}$. The indirect emission reduction TSP is 1095 t/a, giving a reduced PM_{10} emission rate at the power plant stacks of 6.08 $g \cdot s^{-1} stack^{-1}$.

Project no. 4, **Top gas pressure Recovery Turbine (TRT).** The project enables electricity production from excess pressure of blast furnace gas at the top of the furnace No.3. The capacity of the power generator is 6,000kW. Emission of TSP is reduced with 96t/a, and the SO_2 emission is reduced with 486t/a. All of this is indirect emission reduction; there is no direct reduction from this project. The emission reduction is therefore so small that no further calculations have been made on this project. The cleaner production plan puts the project in the central heating category.

5.2 District heating project

Project no 5, **District Boiler House (DBH)**. District heating is a growing source of heating in Taiyuan like in many other cities in China. The Heat Supply Plan of Taiyuan describes a plan to build 30 big district boiler houses in the city to replace current small and inefficient coal boilers. The first four boiler houses are planned for completion by 2005, although funding is a problem. Using data from the approved boiler house no. 1, we assume that three boilers will be installed in the boiler house with a total capacity of 157,000 kW. The new boilers and boiler house will replace 53 boilers and 16 boiler houses that currently serve a 2 km^2 residential area. The savings are estimated to 28,000 tons of coal annually (20,000 tons of coal equivalents). The new boiler house will emit approximately 220 t/a TSP and will produce steam, mainly in the winter season to replace household coal consumption and coal consumption of small industries in the area. The boiler house stack is planned to be 120 m high and 3 m wide. The flue gas release temperature will be 80 °C. Household emissions of TSP modeled at 12 m release height will be reduced by 380 t/a, and emissions from small industries with release height 30 m will be reduced by 590 t/a. The net annual TSP reduction is thus 750 t/a (970–220). The household emission rate changes from 3.75 $\mu g \cdot s^{-1} m^{-2}$ to 0.087

$\mu g \cdot s^{-1} m^{-2}$. The small industry emission rate changes from 5.69 $\mu g \cdot s^{-1} m^{-2}$ to 0.037$\mu g \cdot s^{-1} m^{-2}$. The emission rate from the new boiler house will be 8.57 $g \cdot s^{-1} stack^{-1}$. The cleaner production plan puts the project in the central heating category. The emissions before and after the project is implemented are listed in Table 5.1.

5.3 Coal briquetting

Project no 6, **Coal Briquetting (CB).** The project consists of four coal briquette plants to produce 1.0 Mton of coal briquettes with desulfurization additives for industrial use. The purpose of this project is mainly environmental improvement. In addition, it increases combustion efficiency by approximately 10% and saves coal. We have estimated the effects by assuming that TSP emissions are reduced 10% from a basis of 8000 tons/year, i.e. 800 tons, because of improved combustion efficiency. In addition emissions are reduced 30% as a consequence of the environmentally improved briquettes compared to raw coal, i.e. 2400 tons/year, for a total of 3200 tons/year or a 40% improvement (Aunan et al., 2004). By similar reasoning the SO_2 reduction is 8640 tons/year. A release height of 30 m has been used for the dispersion modeling. The PM_{10} emission rate will thus be changed for the small industries modeled as area sources covering the city from 5.69$\mu g \cdot s^{-1} m^{-2}$ to 5.07$\mu g \cdot s^{-1} m^{-2}$. The cleaner production plan has the project in the clean coal category.

6 Results

The projects were modeled in AERMOD to see what the effects were on the PM_{10} concentrations. The air quality improvements are shown in Figure 6.1 and Figure 6.2. The figures show the average annual concentration reductions in $\mu g/m^3$ for all the measures except project 5, which will only influence the air quality in the winter season. For this project the concentration reduction is averaged over the winter. The estimates make it clear that the location and nature of the source are of equally great or even greater importance than the net emission reduction.

From Table 5.1 we can rank the projects after falling emission reductions with the largest reduction in project 6 and the smallest in project 1, disregarding project 4.

Project 6 > Project 2 > Project 3 > Project 5 > Project 1

When, on the other hand, we look at the effect on the local air quality we find that the measure having the largest PM_{10} reduction is not necessarily the most potent.

When looking at the concentrations, it is somewhat harder to rank the measures. The largest effects are found in projects 2, 5 and 6. These are all projects where the emission reduction is at levels 30 m or lower.

If we consider the measure with the highest peak concentration reduction as the best, that would be measure 2 at the Iron & Steel Company, with project 5 second and project 6 in third place. However, projects 2 and 5 are very local, and hence the concentration reduction drops quickly, whereas project 6 affects the whole city and gives a more evenly distributed effect. It could be argued that project 2 is the best even though the concentration reduction drops quickly, simply based on the fact that the peak level is almost 100 times larger than in project 6, and therefore even a quick reduction in concentration will give comparatively large values at the city limits. Project 5 has a 10 times higher peak value than project 6, but then it drops quickly. This project is also only an improvement to the air quality in the winter months, so it is fairly safe to say that project 6 is more potent than project 5.

The smallest effect is not surprisingly found in project 1. This is by far the smallest project in terms of emission reduction, and the reduction is from tall stacks so that the emission is fairly diluted when it reaches the ground. However, it must be kept in mind that we have not considered effects outside the city. These will surely be small at each location, but are likely to extend over large areas.

The second smallest effect is found in project 3. This project was ranked third from the emission reduction view, and could at first glance seem more potent than it actually is. The reason is again that the reduction is from tall stacks, diluting the pollutant before it reaches the ground.

From these arguments we could rank the projects as:

Project 2 > Project 6 > Project 5 > Project 3 > Project 1

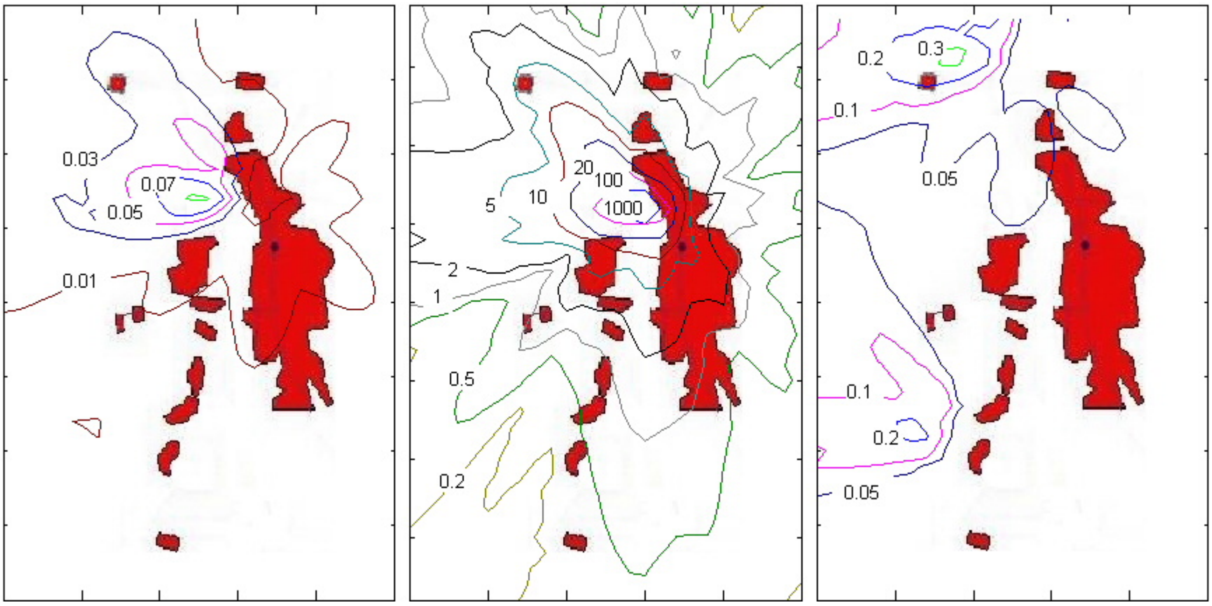

Figure 6.1 Annual average PM10 concentration reduction (μg/m3) from projects 1-3 at Taiyuan Iron & Steel Company. Project 1 to the left, project 2 in the middle, and project 3 to the right. The gray parts show the urban areas of the city.

To rank abatement measures, some criteria are needed. A concentration reduction alone is of little use if nobody or nothing is affected by it. Different end points can be chosen, e.g. increased crops, reduced damage to materials and buildings or improvement of health to the population. An integrated assessment of the projects is presented in (Mestl et al., 2004). There the health benefits of the measures are chosen as end points. To estimate changes in human exposure we have to know the population density throughout the modeling area. The results from the dispersion modeling can then be combined with the estimated population densities, giving estimates of how the exposed population throughout the city will be influenced by the abatement options.

From the resulting exposure distribution, we can calculate the weighted population exposure reduction for each option (ΔPWE). ΔPWE for an abatement option is calculated on an annual basis as:

$$\Delta\text{PWE}=\frac{1}{P}\sum_i \Delta m_i \cdot p_i$$

where p_i is the population in area i, Δm_i is the reduction of the pollutant in area i, and P is the total population in the city. Use of the population weighted exposure reduction is warranted because the exposure-response functions are linear or close to linear in the relevant range of exposure reduction. In our case, a ranking based on ΔPWE gives the same results as our discussion above, though projects 5 and 6 are equal within the uncertainty.

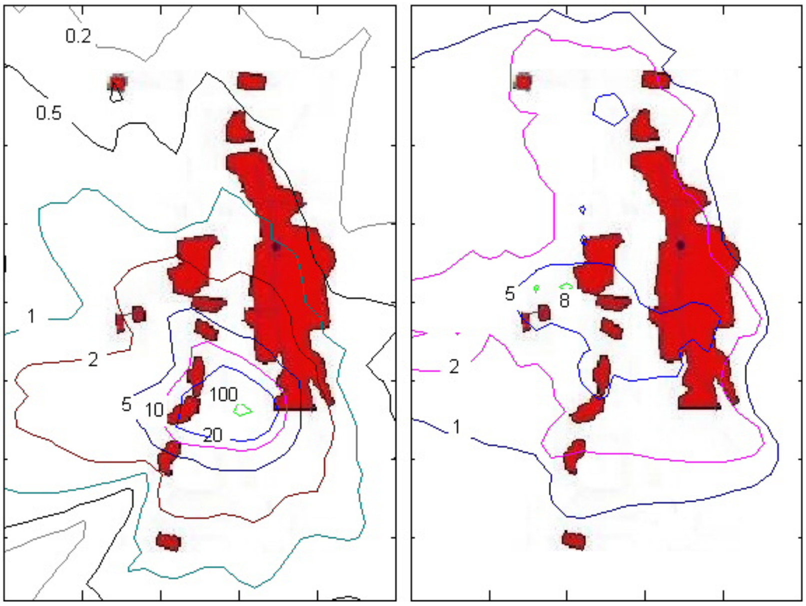

Figure 6.2 PM10 concentration reduction (μg/m3) from measures 5 and 6 in Taiyuan. For project 5 (left) the concentration reduction is averaged over five winter months (November–March), and for project 6 (right) it is the annual average. The gray parts show the urban areas of the city.

Exposure-response functions for a range of different health effects ('end-points') were used to estimate the health impact, and a monetary valuation based on (Aunan and Pan, 2003) was used to compare the economic impact of the projects in (Mestl et al., 2004).

7 Sensitivity

The modeling is associated with large uncertainties. Apart from the intrinsic uncertainty of the model, the input data are uncertain. The meteorological input is based partly on measurements, partly on assumptions, and partly on tabulated data. The emission data are as far as possible based on interviews and reports, but obviously it is hard to get all the data that could be needed for such modeling, and therefore some assumptions had to be made. The modeling was tested for its sensitivity to the meteorological input and the emission data.

7.1 Sensitivity to meteorological input

The model was tested for its sensitivity to the input meteorological parameters: albedo, surface roughness length and Bowen ratio. The change was measured for the peak concentration in the city and the average concentration. The tests were run for measure 5. This was chosen because it has all types of sources included. Area sources at 10 and 30 m representing households and scattered industries, and one stack at 120 m. The test showed that the results are very robust with respect to Albedo and Bowen ratio. As is seen in Table 7.1, the parameters were altered ±20%, but the results showed a maximum of 0.3% change in both the peak and mean concentrations. The results turned out to be more sensitive to the choice of surface roughness length. The surface roughness length was also altered ±20%, and in addition one run was made where the value was doubled. We found that with a doubling of the surface roughness length, the mean concentration was reduced by 28%. A 20% change gave a maximum of 8% increase in the mean concentration. Thus the results are sensitive to the choice of surface roughness length, and caution should be shown in the selection.

In our modeling we selected the surface roughness length to be 0.5 m. This was based on Taiyuan being a large city, but still having small town characteristics like few tall buildings. Had it been a Western city with the same population (2.4 million), the surface roughness length would probably be larger, in the range of 1 m or even more. We should therefore bear in mind that the choice of the surface roughness length has a certain amount of uncertainty and that the results are somewhat influenced by that choice.

Table 7.1 Change in max and mean concentration when the meteorological constants, albedo, Bowen ratio and surface roughness length were altered ±20%, and surface roughness length was doubled.

	Albedo		**Bowen ratio**		**Surface Roughness length**		
	-20%	**+20%**	**-20%**	**+20%**	**-20%**	**+20%**	**+100%**
Change in peak concentration (μg/m3)	0.1	-0.3	0.007	-0.005	2.44	-2.83	-16.90
% Change in peak concentration	0.1	-0.3	0.006	-0.005	2.1	-2.4	-14.5
Change in mean concentration (μg/m3)	0.005	-0.0004	0.0004	-0.0003	0.19	-0.16	-0.69
% Change in mean concentration	0.2	-0.02	0.01	-0.01	7.9	-6.4	-28.1

The meteorological data were, as mentioned in section 3, downloaded from (WeatherOnline, 2002). This site provided us with the necessary hourly measurements, but did not contain upper air soundings. Therefore we had to construct these soundings based on average meteorological conditions. To test the robustness of the results according to these constructed data, we constructed two alternative upper air soundings. The first was made with neutral atmosphere, i.e. the temperature decreases with -1 °C/100 m. The second was made with neutral temperature up to 500 m and then an inversion with 1 °C/100 m up to 1000 m. These tests gave no changes in the results, and we conclude that with our data availability the model only lays minor importance to the input upper air soundings when calculating the parameters of the mixing layer.

Finally we downloaded meteorological measurements of the following year, November 2001 to October 2002, to see if there were significant differences between the two years. All the abatement projects were run with the new year and compared to the base year. From Table 7.2, we see that there are differences, but that the overall results give good consistency between the years.

Table 7.2 Comparison of the years Nov. 2000-Oct. 2001 and Nov. 2001-Oct. 2002.

	Project no. 1	**Project no. 2**	**Project no. 3**	**Project no. 5**	**Project no. 6**
Change in peak concentration (µg/m3)	0.004	113.5	0.015	15.98	0.4
% Change in peak concentration	3.8	10.1	4.8	13.7	4.4
Change in mean concentration (µg/m3)	0.0005	0.4	0.002	0.3	0.1
% Change in mean concentration	4.3	9.7	4.6	10.8	5.7

7.2 Sensitivity to emission data

AERMOD is, as earlier mentioned, primarily made for modeling in the US and other Western countries, where the data availability is good. To get a full emissions inventory even in a Western city would at best be difficult, and in China it is simply not possible. We therefore had to base the emissions partly on reports and interviews, and partly on assumptions. The error made in the estimates due to our assumptions will be tested and presented in this section.

For the large industries included in the modeling, we had a report on the emissions. However, that report did not give all the necessary stack information. Therefore we were forced to make some assumptions.

For the two power plants we were able to get fairly accurate stack information, so we believe that they are modeled well. For the Coal and Power Company and the Heavy Machinery Company we know that there are many stacks involved and they have heights ranging from 20 to 60 m. We modeled each with one stack at 40 m. The error from this has not been scrutinized, because the relative contribution to the air quality of Taiyuan from these emitters is small.

At the Iron and Steel Company we do know that there are 54 stacks at heights ranging from 20 m to 120 m, and that there are 25 different sources of process dust. The detailed data was not possible to retrieve, so we had to make several assumptions.

The data for the process dust was particularly unclear, and this influenced one of the projects that we studied directly. Therefore we tested the assumptions of project no. 2, and at the same time got an impression of the effect of the error in the process dust modeling.

In project no. 2 we know that there are six stacks, and we have the emission data for them. We also know that they will be replaced with one or more tall stacks with low emission rate due to cleaning technologies. Details of replacing stack design are thus of small relative importance as long as we know that the stack will be tall and with only small emissions.

The dust emissions on ground level in the factory hall are very uncertain. We know the amount steel produced, but not the emissions. The emission factor of steel production ranges from 10 to 15 kg-TSP/ton of steel. Then we don't know the PM_{10} share of this dust, or the design and draftiness of the factory hall, so we don't know the amount of PM_{10} that is added to the outdoor air, and finally we don't know the emission height.

We did three test runs for comparison to the project base case. One where we increased the PM_{10} emissions at ground level, simulating a higher PM_{10} share or more drafty factory hall or a higher emission factor, and one where the ground level emissions were decreased simulating a lower PM_{10} share or more air-tight factory hall, and finally we tried to increase the emission height from 5 to 8 m. We see from Table 7.3 that a change in emission rate gives a direct and proportional change in concentration. A 23% change in emission rate gives a 23% change in peak and mean concentration. A 3 m or 60% increase in emission height alters the peak concentration by 22%, and the mean value by 10%.

Table 7.3 Change in max and mean concentration for project no. 2 when the emission rate and height are altered.

	Height changed +3m	**PM10 emission rate**	
		-23%	**+23%**
Change in peak concentration (μg/m3)	-243.12	-256.12	256.12
% Change in peak concentration	-21.6	-22.8	22.8
Change in mean concentration (μg/m3)	-0.41	-0.94	0.94
% Change in mean concentration	-9.8	-22.5	22.5

Finally we examined the uncertainty of the emission data of the household and 'small industries'. The uncertainties of the two are similar and we therefore used the small industry emission data for sensitivity tests. There are important uncertainties in these data regarding annual emissions, PM_{10} share, emission height, and source location. From Table 7.4, we see that a change in emission rate gives a proportional change in concentration. Moving the sources more to the outskirts of the city only gives minor changes to the mean concentration, but the concentration pattern is changed and influences the exposure to the population (Mestl et al., 2004). In the base runs the emissions were assumed to occur between 20 and 40 m. We also made runs varying both average emission height and the height interval where emissions occur. The model run with height interval 25–35 m gave a slightly reduced concentration compared to the base run. Decreasing the height by 10 m increased the concentration by approximately 50%, while a 10 m increase in the height resulted in a reduction of about 25%.

Table 7.4 Sensitivity to emission height, rate and pattern. Tested for project no. 6, coal briquetting.

	Height 30 m (5 m	**Height 20 m (10 m**	**Height 40 m (10 m**	**Other source locations**	**Emission rate –27%**	**Emission rate +27%**
Change in peak concentration	0.09	4.6	-2.2	-2.2	-2.4	2.4
% Change in peak concentration	1.1	53	-25	-25	-27	27
Change in mean concentration	-0.08	0.9	-0.5	-0.1	-0.5	0.5
% Change in mean concentration	-4.2	49	-28	-5	-27	27

8 Discussion

AERMOD was primarily made for dispersion modeling in the US and other Western countries. The model therefore relies on large amounts of input data. In a city like Taiyuan, data availability is limited. We showed that even with our restricted data, the model could be successfully utilized. Tuning of the model to give good agreement to the monitored data can be seen as a quality test of the abatement projects. We saw that the estimated concentrations, both mean and peak, are directly proportional to the emission rate, thus the uncertainty of the emissions reduction of a project is also the uncertainty of the estimated concentration. The emission height is also crucial to the results, whereas other parameters are less sensitive. The meteorology of two consecutive years gives larger discrepancy in the results than the choice of meteorological constants, except for the surface roughness length, which is of the same order.

The main advantage of using the model is that it gives a clear picture of what kind of sources are the most potent in terms of improving the local air quality. Large emission reductions in tall stacks give only limited local air quality improvement, whereas smaller reductions close to the ground give large improvements. This is in agreement with earlier work by others (Smith, 2002). In the future one should therefore not necessarily seek measures at large industrial facilities where the emissions are from tall stacks, but maybe shift the focus to smaller scale projects improving emissions closer to the ground. However, it must also be considered that reductions in emissions from tall stacks result in concentration reductions that are small, but cover large areas. The related effects are not included in this study.

Reference List

Aunan, K., Fang, J, Vennemo, H, Oye, K, and Seip, H. M. (2004) Co-benefits of climate policy - lessons learned from a study in Shanxi, China, *Energy Policy* (In press)

Aunan, K. and Pan, X (2003), Exposure-response functions for health effects of ambient air pollution for China - a review, (Submitted)

BP (2003), BP statistical review of world energy 2003. Available on: http://www.bp.com/centres/energy/index.asp

EQRT (2000), Environmental Quality Report for Taiyuan, *Environmental Monitoring Centre of Taiyuan*

Gan, L. (1998), Energy development and environmental constraints in China, *Energy Policy* 26(2) 119-128.

He, K. B., Huo, H., and Zhang, Q. (2002), Urbab air pollution in China: Current status, characteristics, and progress, *Annual Review of Energy and the Environment* 27 397-431.

NILU/NORAD (2001), Inception report. Unpublished work.

Mestl, H E S, Aunan, K., Fang, J, Seip, H M, Skjelvik, J M, and Vennemo, H (2004) Cleaner production as climate investment - Integrated assessment in Taiyuan City, China, *Journal of Cleaner Production* (In press)

Riley, W J, McKone, T E, Lai, A. C K, and Nazaroff, W W (2002), Indoor particulate matter of outdoor origin: Importance of size-dependent removal mechanisms, *Environmental Science & Technology* 36(2) 200-207.

SEPA (2000), Report on the state of the environment in China 1999. Available on: http://www.zhb.gov.cn/english/SOE/soechina1999/air/air.htm

Sinton, J. E. and Fridley, D. G. (2000), What goes up: recent trends in China's energy consumption, *Energy Policy* 28(10) 671-687.

Sinton, J. E., Levine, M. D., and Wang, Q. Y. (1998), Energy efficiency in China: Accomplishments and challenges, *Energy Policy* 26(11) 813-829.

Smith, K. R. (2002), Place makes the poison: Wesolowski Award Lecture - 1999, *Journal of Exposure Analysis and Environmental Epidemiology* 12(3) 167-171.

SSAAT (2002), A Study on Source Apportionment of Aerosols in Taiyuan, *Taiyuan Design Institute of Environmental Science; College of Environmental Science and Engineering at Nankai University; Taiyuan Environmental Monitoring Station*

Taiyuan Government (2001), Government report Taiyuan.

US-EPA (1998a), Revised Draft User's Guide for the AERMOD Meteorological Preprocessor (AERMET), *U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards*

US-EPA (1998b), Revised Draft User's Guide for the AMS/EPA Regulatory Model -AERMOD, *U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards*

WeatherOnline (2002), *WeatherOnline UK & Ireland, Meteorological services*. Available on: http:www.weatheronline.co.uk

Zhang K, Son J, and Han Y (2003), A brief introduction on Clean Energy Plan in Taiyuan, Shanxi Energy and Conservation, No.1 1-4.

APPENDIX

Coal consumption and emissions.

Table A1. Emission factors. From (Aunan et al., 2004)

	EF(TSP) kg/ton	EF(SO_2) kg/ton
Households	20	20.2
Industry		
Power	3.6	18.1
Coke making	2.9	5.0
Ind. combustion	8.0	18.1

There are no comprehensive reports on the total coal consumption and emissions in Taiyuan. Thus we had to combine the information that was possible to retrieve.

The total reported industrial SO_2 emissions are 198,000 t/a (NILU/NORAD 2001). Of that the five industries treated as point sources emit 125,000 t/a. The remaining industries thus emit

198,000–125,000 = 73,000 t/a

With an emission factor of 18.1 kg/ton this gives an industrial coal consumption of

73,000 (t/a)*1000 (kg/ton)/18.1 (kg/ton) = 4,030,000 t/a.

We assume that 80% of this is consumed within the inner city area that is covered in our investigations, i.e.

4,030,000*0.8 = 3,220,000 t/a.

We assume that the commercial consumption is approximately half the household consumption, i.e. 450,000 t/a Thus the consumption for the ‘small industries’ in the inner city is

3,220,000 + 450,000 = 3,670,000 t/a.