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REGIONAL AIR POLLUTION IMPACT: A DISPERSION METHODOLOGY DEVELOPED AND APPLIED TO ENERGY SYSTEMS

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Preface

This report is one of a series describing a multidisciplinary multinational IIASA research study on Management of Energy/Environment Systems. The primary objective of the research is the development of quantitative tools for energy and environment policy design and analysis -- or, in a broader sense, the development of a coherent, realistic approach to energy/environment management. Particular attention is being devoted to the design and use of these tools at the regional level. The outputs of this research program include concepts, applied methodologies, and case studies. During 1975, case studies were emphasized; they focused on three greatly differing regions, namely, the German Democratic Republic, the Rhone-Alpes region in southern France, and the state of Wisconsin in the U.S.A. The IIASA research was conducted within a network of collaborating institutions composed of the Institut fuer Energetik, Leipzig; the Institut Economique et Juridique de l'Energie, Grenoble; and the University of Wisconsin, Madison.

Other publications on the management of energy/environment systems are listed in the Appendix at the end of this report.

W.K. Foell

Abstract

A methodology is presented to account for the dispersion of air pollution emissions at a regional level to arrive at ambient ground-level concentrations. Air pollution due to energy is a major concern. This methodology has particular relevance to studies of alternative futures and to long-range environmental policy analysis. The methodology is developed using detailed dispersion model results and a Smeared Concentration Approximation (SCA) Dispersion Model is derived for Wisconsin using the methodology. A preliminary validation for sulfur dioxide and particulate matter pollution indicates that the methodology provides a reasonable picture of the urban air pollution concentrations. Results are presented to demonstrate that dispersion is important and relative impact is not at all proportional to a sector's percentage of total emissions. The results of the use of the SCA method in specific case studies indicates the value the method has for addressing air pollution impacts.

Acknowledgements

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INTRODUCTION

The Need

Information on energy-related environmental impacts is essential to long-range planning and policy design at the regional level. Of particular importance are data on environmental impacts due to air pollution. Energy use and air pollution are strongly correlated, especially for SO_2 pollution, and as many regions grow economically and demographically, so too grow their air pollution problems. The awareness of the importance of air pollution impacts has grown together with the recognition of the importance of environmental management as a component of the planning process. Some prominent policy questions now being asked are:

1) What are the major sources of ambient pollution concentrations in an airshed?
2) What is the effect of various pollution control strategies on air pollution concentrations?
3) What is the correlation between urban patterns and air pollution concentrations?
4) What are the advantages of concentrating primary energy use through such conversion methods such as electricity generation and district heating in terms of air pollution characteristics?
5) What effect do reduced energy consumption patterns have on air pollution concentrations?

Emissions have frequently been the sole indicator of air pollution in long-range policy design efforts, mainly because of the difficulty in extending a simple analysis to the calculation of ambient air pollution concentrations. It is costly both in time and money to develop detailed emission inventories and to make the detailed dispersion model calculations needed for the environmental impact analysis. Also, the level of detail provided in this manner is often much greater than that needed by the decision maker concerned with broad policy design over the long term.

However, emissions are not a good indicator of regional air pollution impact. A power plant may have significantly greater emissions of a pollutant than all other sources combined in a given urban area. But, the power plant may be responsible for only a small fraction of the ground-level air pollution concentration for that pollutant in the urban area. Yet it is the ambient air pollution concentration at ground level that causes many of the environmental impacts, not the emissions. In other words, the magnitude of the contribution of an emission source to the ambient ground-level concentration of an area is not directly related to the magnitude of its contribution to the total emissions in the area. This is because the dispersion characteristics (the way the pollutants mix into the air) are quite different for different types of sources, for example households versus industry. Even within one class of sources, such as industry, there may be great differences in the dispersion characteristics among individual sources. Hence, a judgment concerning the sources of air pollution impacts for regional planning decisions may be totally incorrect if based on air pollution emissions. It is important to include the dispersion of air pollution emissions in the analysis of regional environmental impacts.

One of the models developed for regional environmental impact analysis and policy design examination is the WISconsin Regional Energy Model (WISE) constructed by the Energy Systems and Policy Research Group at the University of Wisconsin [1]. As a major component of WISE, a methodology for the systemwide assessment of energy-related environmental impacts, with specific reference to electricity generation, was developed at Wisconsin and IIASA [2]. Further work, incorporating the dispersion of air pollution emissions from coal-fired electricity generating plants into this methodology, was done at IIASA [3].

Additional effort at IIASA has also been expended to develop a methodology to include air pollution dispersion for non-electric energy-related emissions in the air pollution analysis of environmental impact. This extension was done by developing an approximation method, described in this paper, for determining the dispersion of air pollutants from the different sources.

The major objective of such an approximation method is to provide a flexible and simple means for calculating ambient air pollution concentrations for use in the analysis of alternative energy futures at the regional level. The air pollution dispersion model prescribed by the approximation method, together with a damage function, provides a valuable tool for long-range policy considerations.

The Requirements

The WISE Model provides an excellent backdrop for the design of such a dispersion methodology. The WISE Model is a computerized dynamic simulation model designed primarily for intermediate-to long-range planning analysis; that is, a time horizon of five to fifty years. The WISE structure is centered around scenario building at the regional level [4]. Scenario building is the detailed development of a set of possible future occurrences for a system for given specific assumptions about the system. The focus of the scenario writing for WISE is regional rather than national because of the former's value in addressing environmental issues--often regional in nature.

One objective of the scenario analysis is to describe the sensitivity of energy usage and environmental impacts to the natural, socio-economic and technical infrastructure of a region. Such a sensitivity analysis implies changing a given parameter of the system or changing one (or a consistent set) of the assumptions about the system, computing a new scenario and analyzing the changes that resulted. This places a great emphasis on the systematic comparison of various alternative policies or alternative combinations of assumptions. Therefore, a simple and flexible means for calculating ambient air pollution concentrations in a region is required. Moreover, the desired methodology must provide sufficient regional detail to be able to address regional environmental impact issues, and yet be able to take advantage of the fact that many local characteristics can be homogenized across the region when examining the region as a whole.

Work has been going on to evaluate ambient air pollution concentrations for a region or a metropolitan area [5,6,7,8,9,10]. But, in general, this work is very detailed, complex, and time- and site-specific. Therefore, it is not suitable for inclusion in a methodology based on scenario writing for the purpose of intermediate- and long-range planning analysis. A more flexible methodology to calculate ambient air pollution concentrations in a region is required.

Several requirements for the characteristics of the methodology derive from its inclusion in scenario analysis, a procedure which necessitates analysis of both individual scenarios and the comparisons across alternative scenarios. For example, the environmental impact analysis of a particular scenario might be concerned with the relative contributions of different emission sources to the air pollution concentrations at the ground level in a particular area. The comparative analysis would be concerned with the changes in the relative contributions of different emission sources for the ground level concentrations that occur when certain scenario parameters are changed and new scenarios are calculated. Another example of a comparative analysis would be the evaluation of different air pollution control strategies.

The methodology is required to provide sufficient detail in its calculations of air pollution concentrations that a meaningful analysis of a scenario and meaningful comparisons between scenarios can be made. This means that detail is necessary concerning the different types of sources. It also means that detail is necessary concerning the geographic location of the sources, because the air pollution concentrations strongly depend on whether the emissions sources are clumped together, as in cities, or are uniformly spread across the region. Yet the detail of the methodology should not be overly complex. It should take advantage of simplifying assumptions that can be made because the scenario analysis is not site-specific within the region. Finally, the methodology must be amenable to the time frame of the scenarios and yet be compatible with any limitations of time and human resources available for an air pollution impact analysis. These considerations form the framework of the methodology.

This paper describes the "Smeared Concentration Approximation" (SCA) method, a methodology developed at IIASA for calculating the dispersion of air pollutants. The method was developed to treat sulfer dioxide (SO_2) pollution, but it is, in principle, also applicable to non-reacting chemical species such as particulate matter (PM) and carbon monoxide (CO). The paper is organized into the following sections. The second section discusses the framework of the SCA method. The third section presents the basic assumptions of the SCA method, and for validation purposes, makes preliminary comparisons of the results of the SCA model developed for Wisconsin with monitoring data and detailed dispersion model calculations for Wisconsin. In addition, some examples are given of the initial application of the SCA method. In the final section, the conclusions are outlined concerning the value and use of the SCA Method for air pollution impact assessment at the regional level.

FRAMEWORK OF THE SCA METHODOLOGY

Based on an analysis of the requirements set forth above, three cornerstones can be defined for the framework of the SCA methodology. These are:

1) Emissions sources need to be subdivided into three distinct classifications.
2) Urban areas should be explicitly modeled.
3) The most reasonable temporal scale is one year.

These cornerstones are explained below.

Emissions Sources

For the development of the dispersion methodology, we have defined three "classes" of emission sources as follows:

1) Area (or low-level) Sources, as for example, transportation and residential emissions;
2) Medium-level Point Sources, as for example, industrial and central or district heating stacks; and
3) High-level Point Sources, as for example, large electricity generating plants.

We refer to the above as three separate classes of emissions and dispersions (see Figure 1).

The need to divide the emission sources into classes is motivated by two different sets of considerations - applicability of the SCA method to widely differing regions and responsiveness of the method to policy questions. The applicability and transferability of the methodology from one region to another is tied to meteorological considerations. In general, the dispersion character of high-level point sources (such as electric power plants), medium-level point sources (such as industrial plants), and area sources (such as home furnaces or automobiles) differ from each other even under similar meteorological conditions. Thus better transferability and flexibility is maintained in the methodology by disaggregating the sources into these classes.

From a policy viewpoint, point sources of pollution, such as power generation facilities or industrial facilities, require a different type of control strategy than would be applied to area sources. Moreover, when evaluating impacts, one would like to assign relative responsibility. Therefore, it is important to know the contributions of each class of source to the ambient pollution concentration; is the source of air pollution mainly industry, automobiles, home heating, etc.? The three classes defined in the SCA methodology give a minimum set that has relevance to such policy considerations.

Spatial Resolution

In the SCA method we explicitly separate out urban areas and calculate urban ambient ground-level concentrations for them. Air pollution damage occurs at or near the earth's surface, i.e. the level of plant, animal and structure contact. Additionally, emissions sources are concentrated in or around urban areas. Once the "edge" of a set of emission sources is reached, i.e. a city boundary, the surface concentrations fall rapidly, as illustrated in Figures 2a and 2b for St. Louis, a medium sized city located in the central United States. For ground-level ambient pollution concentrations, this means that cities or urban areas are "islands" protruding from a "sea" of rural background pollution concentrations.

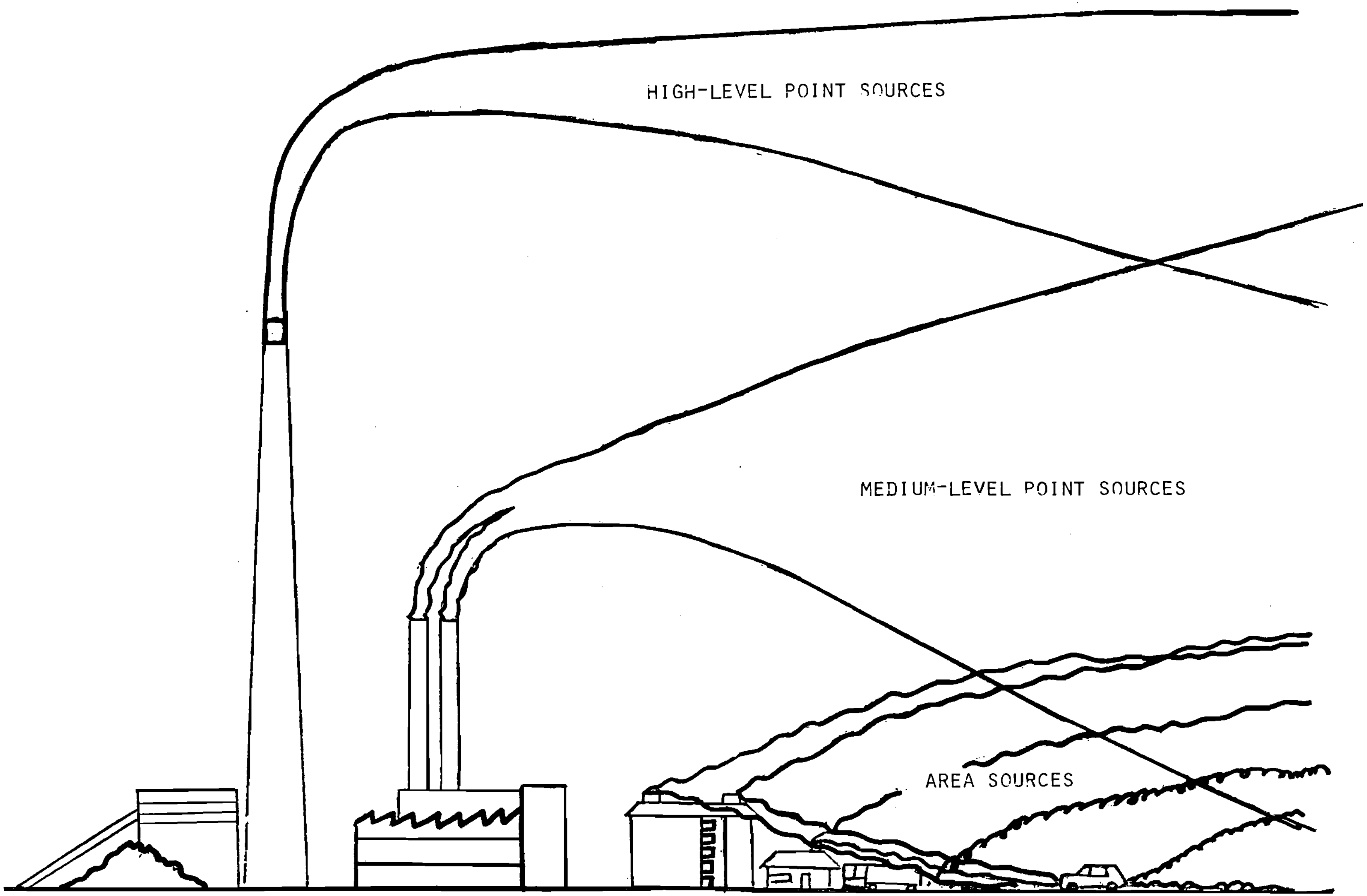

Figure 1: Types of Emission Sources

Wind = 4.9 Meters per Second; Stability Index = 0.25; Mixing Height = 540 Meters

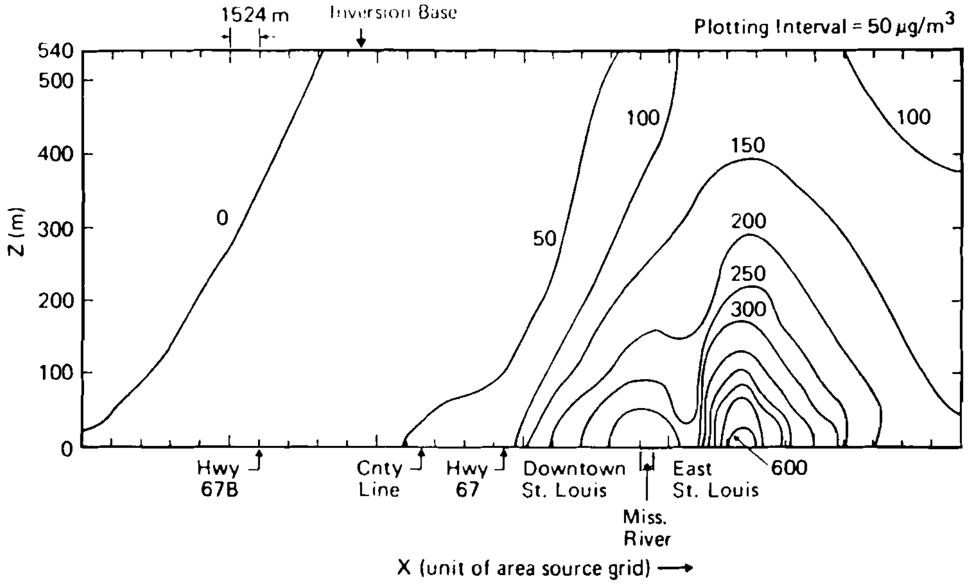

Figure 2a: Simulation of Hourly Averaged SO_2 Concentration Field In the x-z Plane for St. Louis.

Wind = 2.2 Meters per Second; Stability Index = 2.2; Mixing Height = 700 Meters

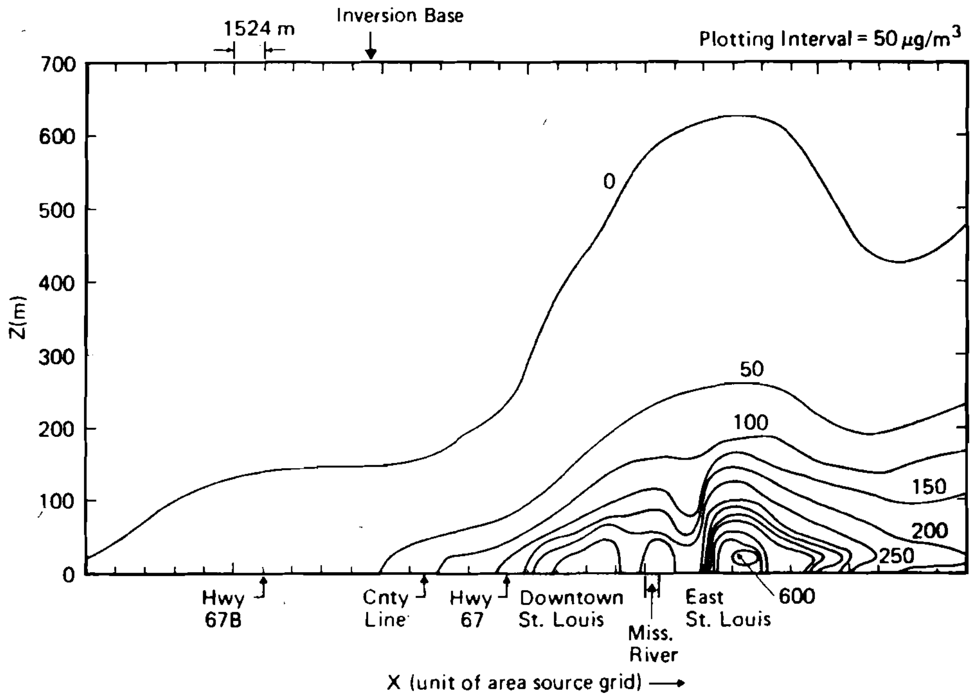

Figure 2b: Simulation of Hourly Averaged SO_2 Concentration Field In the x-z Plane for St. Louis.

Figuratively, the depth of the background sea, the absolute height of these islands, and their height relative to that of the background are the important indices. This means that a methodology for analysis of regional pollution dispersion must explicitly treat these islands. The method of treatment can vary from modelling each urban area separately to grouping the urban areas into a small number of classes and modelling these classes; or it can be flexible enough to incorporate some combination of these two.

Time Frame

A number of factors must be considered for determining the temporal scale that is most relevant for the SCA method. Long-term policy considerations with respect to environmental impacts are concerned with changes in indices for intervals of one to several years. Damage functions usually relate to ground-level pollution concentrations averaged over one year or less. For some health impact models [11], twenty-four hour averages for each day of the year are necessary. Larson [12] has observed that the frequencies of occurrence of air pollution concentration can be approximated as log-normal distributions; thus any short-term average can be derived from the annual average using the geometric standard deviation. This is schematically shown in Figure 3 for twenty-four hour averages where the slope is related to the geometric standard deviation. The most common denominator in the reporting of air pollution data for SO_2 is the annual average concentration. Consideration of the above factors lead to the methodology being based upon the calculation of the annual average ground-level pollution concentration with conversion to shorter period averages where required.

SMEARED CONCENTRATION APPROXIMATION METHOD

The Smeared Concentration Approximation (SCA) method represents the ground-level ambient pollution concentration of an urban area by a single concentration uniformly "smeared" over the urban area. That is, the urban islands of air pollution are converted to "pill boxes" of constant height added to a flat rural background

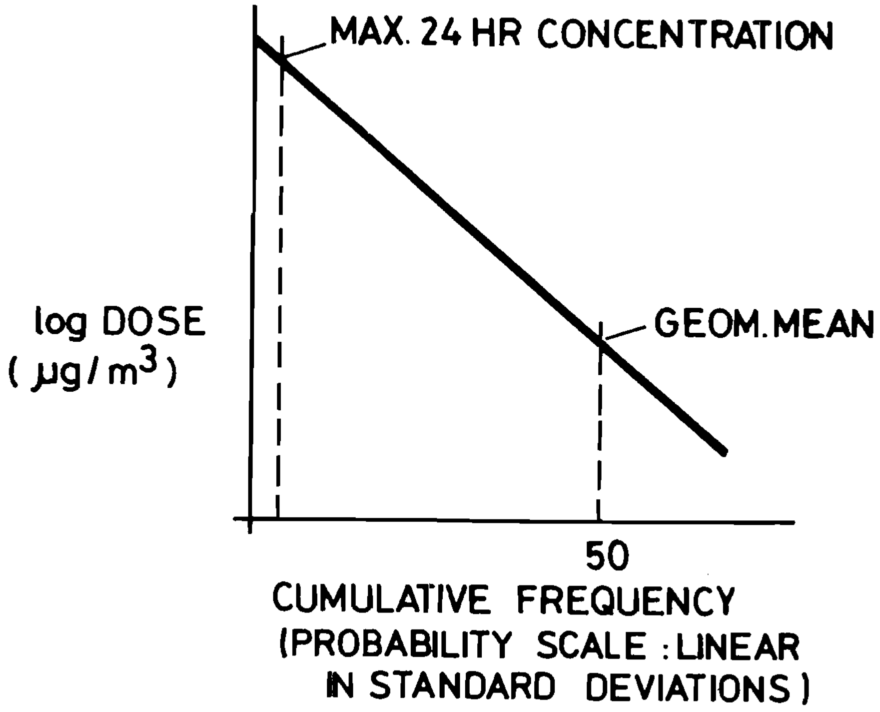

Figure 3: Log-normal Relationship Between Annual and Twenty-Four-Hour Averages.

pollution concentration as illustrated in Figure 4.

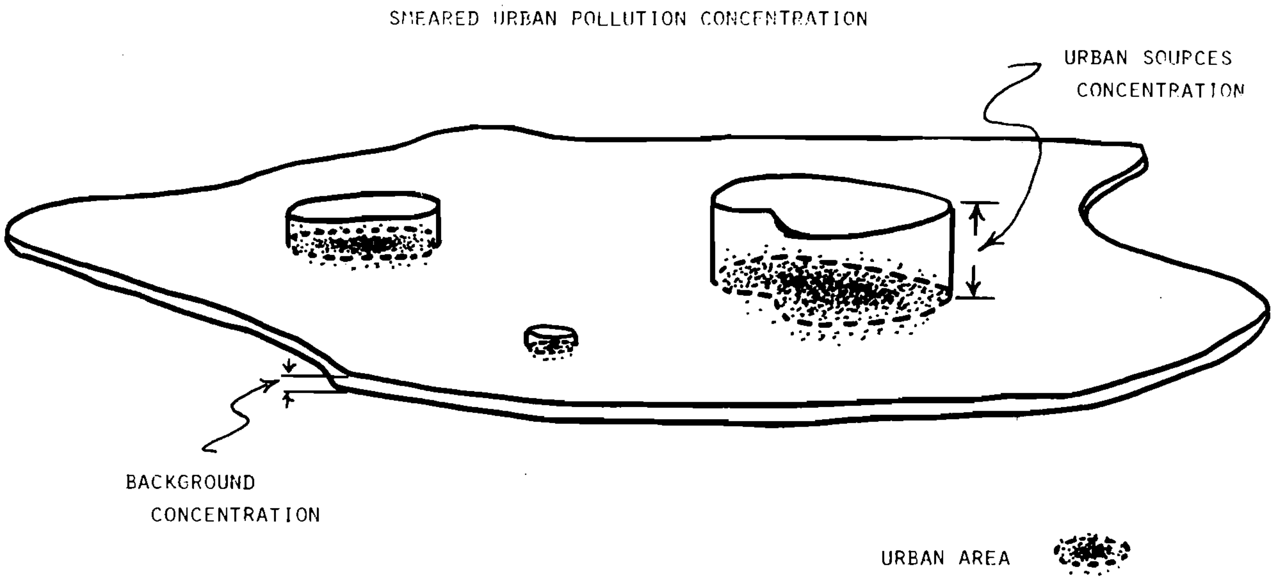

Figure 4: Smeared Urban Pollution Concentration Adding to a Flat Rural Background Concentration.

The expression of this average concentration for each urban area as the sum of a rural background concentration and three urban source concentrations is shown in Equation 1.

$$C = B + \sum_{i=1}^{3} C_i \tag{1}$$

The calculation of the rural background concentration, B, will be discussed later in the report. The urban source concentrations C_i, are calculated for each of the following classes of emission sources:

$i = 1$: Area Sources,

$i = 2$: Medium-Level Point Sources, and

$i = 3$: High-Level Point Sources.

The annual average concentration for an urban area, C_i, is calculated as shown in Equation 2 by multiplying the total annual urban emissions, E_i^u, in class i by an SCA dispersion parameter, D_i, defined for class i.

$$C_i = E_i^u D_i \tag{2}$$

Until recently it was difficult to develop reliable dispersion parameters, such as the SCA dispersion parameters, D, especially in the case of area sources [13,14]. The work has been more successful in the case of point sources [15,16,17], even though physically untenable assumptions for atmospheric parameters are embodied in the analytical models. Second generation dispersion models for area-type emissions have now been built and tested to the extent that their results can be used with a good degree of confidence. The most useful of these models for resolving ground-level pollution concentrations for urban area sources are the three-dimensional box models[1] [8,9,10,18]. However,

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[1] Three-dimensional box models as used here are numerical models based on a concentration diffusion equation for a rectancular Eulerian coordinate system. The governing equation is based on the conservation of mass law for a steady flow of a pollutant with the turbulent diffusion in the vertical direction represented by a gradient diffusion (Fick's Law).

several adaptations of analytical Gaussian plume models have also been used to calculate ground-level concentrations due to area sources [19,20,21].

In the work described in this report a three-dimensional box model provided the basis for the area source SCA dispersion parameter and a Gaussian plume model provided the basis for the point source SCA dispersion parameters. The basic assumptions for the development of the SCA parameters are described below.

Basic Assumptions

Aggregation and Mobility

We have assumed high mobility of the population within an urban area, relative to the fine structure of the spatial distribution of the pollution concentration. Based on this mobility assumption, one can associate a single concentration/population-dose relationship with an urban area. Admittedly, some districts within an urban area will consistently experience higher pollution levels than the average and since there are threshold effects in some health impacts [11], neglecting these higher levels may result in an underestimation of the health impact. However, compared to the added insight for health impacts gained by the use of the SCA method, such an underestimation is considered tolerable.

Point Source Dispersion and Location

Three assumptions have been made in the development of the SCA dispersion parameters for point source emissions.

1) Rural coefficients of dispersion are adequate for all calculations, even for urban areas;
2) A single set of meteorological statistics is adequate for all urban areas within the region; and,
3) A single representative pattern of industrial-type point sources is adequate for all urban areas within the region.

Coefficients of Dispersion: A multiple-point source Gaussian plume model was used to calculate the SCA point source dispersion parameter. Although this model has some weaknesses, it is easy to use and represents ground-level pollution concentrations well [17]. A key parameter of the model is the coefficient of dispersion, σ, used to represent the vertical turbulence. This parameter is sensitive to the surface roughness; i.e. whether the dispersion occurs over grass (relatively smooth) or over a city with tall buildings (relatively rough). Given the population mobility assumption stated earlier, a single average concentration is used for the entire urban area. Since in calculating the SCA dispersion parameter this average is not very sensitive to changes in the surface roughness, and because the most reliable coefficients of dispersion have been developed for rural-type roughness [5], we have used the rural coefficients of dispersion in our point source calculations for both rural and urban areas.

Meteorological Statistics: In order to calculate ambient pollution concentrations at specific points in a region, the meteorology must typically be changed from site to site if the region is large. However, when the ambient ground-level pollution concentrations are averaged for entire urban areas, the differences among urban sites as a result of meteorology are less important, particularly if the topography of the entire region is reasonable uniform. Therefore, we use only one representative set of meteorological statistics in the multiple-point source Gaussian plume model to derive the set of SCA dispersion parameters that will be applied to the entire region.

Point Source Location: Sensitivity calculations on point source location for a rather symmetric pattern of point sources were carried out at IIASA. The emission pattern of the point sources, however, was not symmetric. These calculations showed, for the same pattern of point sources, that when the concentrations are averaged over a representative urban area, the results are insensitive to the distance between the point sources, even though this distance changes by over two orders of magnitude.

Of course urban areas do not all have industry distributed more or less equally throughout the area. Urban areas may have industry more heavily located in one section and depending on the prevailing winds, the average concentration due to the industrial point sources may be above or below the average calculated for a more symmetric distribution of industrial point sources. However, industrial location is not solely determined by air pollution considerations and when an actual region is considered, many of these differences will cancel out. This cancelling out is further enhanced by the mobility assumption above. Based on the cancelling out assumption and the sensitivity calculations, one can reasonably apply a single representative pattern of point sources to all urban areas in the region.

Area Source Dispersion

Normally, the size of an urban area influences the buildup of the ground-level concentration for a given density of emissions and the SCA dispersion parameter would be a monotonic function of city size. At this point in the development of the SCA method, we have chosen to use one representative area source SCA dispersion parameter for all urban areas. The reasons are discussed below.

As previously stated, the most useful type of numerical model with which to calculate the area source SCA dispersion parameter is the three-dimensional box model. However, there is a lack of systematic box model calculations that can be used to account for the influence of the urban size on the SCA dispersion parameter. Moreover, without emission inventories for several cities in one region, it is not possible to extract this effect from the monitoring data available. Thus the task is to define a reasonable range of city areas with which one could make the box model calculation that will give a representative area source SCA dispersion parameter.

Preliminary indications from work done at Wisconsin [22] are that the effect of urban size on the SCA dispersion parameter would be most pronounced for urban areas less than 5 km in radius and that the size effect would begin saturating for cities of radii greater than 10 km. Saturation of the size effect can be illustrated by examining a uniform area source of emissions for the very common meteorological conditions of a neutral atmosphere and low wind speeds. For a given radius of the area source, r, the increase ΔD, of the SCA dispersion parameter, D, for a Δr of 1 km; exhibits the following behavior:

$r = 2$ km	$\Delta D = 28\%$
$r = 3$ km	$\Delta D = 14\%$
$r = 5$ km	$\Delta D = 6\%$
$r = 7$ km	$\Delta D = 3\%$
$r = 10$ km	$\Delta D = 2\%$
$r = 15$ km	$\Delta D = 1.4\%$

The leveling off of ΔD after a rapid decrease, to small percentages as the radius increases is what is termed the "urban size saturation effect". Beyond a radius for the area source of 7-10 km, the increase in the SCA dispersion parameter due to an increase in the size of the area source becomes small relative to the other uncertainties involved.

Additionally, using the concept of the exponential city [23], one finds for Western cultures that an urban population of one-hundred thousand inhabitants corresponds to a radius $R = 5.5$ km, five-hundred thousand inhabitants corresponds to $R = 11.3$ km, and one million inhabitants corresponds to $R = 15.3$ km. Since very little of the total impact will occur in cities with populations less than one-hundred thousand, only R values greater than six kilometers are significant in the analysis. Because the urban size effect begins saturating for R equal to ten kilometers it is unnecessary to use an R much greater than ten kilometers. Therefore, a representative range for the radius of the urban area for the box-model calculation used to derive the area source SCA parameter is six to twelve kilometers.

Rural Background Ambient Pollution Concentrations

For the ambient background pollution concentrations in rural areas, we believe that detailed dispersion models have not yet been sufficiently validated to use them directly as has been done for urban areas. Detailed dispersion models do, however, give a guide to the relative influence, or effective emission strength, of the different emission sources on the rural background pollution concentration. Therefore, to calculate the ambient background concentration in the SCA method the concept of effective emission strength is used together with an initial value for the ambient background concentration.

The effective emission strength, F(E), at a point in time is a linear function of the total emissions in the region from the three classes of emission sources, as shown in Equation 3.

$$F(E) = aE_1 + bE_2 + cE_3 \tag{3}$$

The constants, a,b, and c represent the relative impact each emission class has on the rural background. In the work described here, the constants are determined for a mid-range (15-40 km) influence that would extend out from the urban areas. This should better represent the changes in background concentrations near large urban areas, where the background concentrations are also highest. The constants are calculated by taking an annular section of the dispersion model results, where the inner radius of the annulus is the same as the radius used to calculate the SCA dispersion parameter. Additionally, the change in the rural background concentration due to a change in the total emissions in the region is assumed to be proportional to the change of the effective emission strength, F(E).

Given an initial value at year t_o for the rural background concentration, $B(t_o)$, with corresponding emissions $E_1(t_o)$, $E_2(t_o)$ and $E_3(t_o)$, then the rural background concentration at any other time, t, is given by Equation 4.

$$B(t) = B(t_o) \frac{aE_1(t) + bE_2(t) + cE_3(t)}{aE_1(t_o) + bE_2(t_o) + cE(t_o)} \tag{4}$$

The initial value, $B(t_o)$, must be obtained from empirical data or from an estimate based on other information.

SO_2 Lifetime

SO_2 is not an inert species, and as an air parcel travels the SO_2 concentration decreases; this can be approximated as a first order decay due to both deposition and transformation:

$$\text{Decay Rate} = R = -k_a \cdot \text{Concentration}$$

The estimated SO_2 decay rates developed by the OECD Long Range Transport of Air Pollutants Program [24] exhibit some variation around $k_a = 2 \cdot 10^{-5} s^{-1}$, corresponding to a residence time of about 10 hours. For normal wind speeds, the reaction rate is slower than the advection rate of wind over an urban area. Thus decay rate effects are not important except in episode conditions. The effect of episode conditions on the annual average ambient pollution concentration is generally small, and it will be very small compared to changes in the annual ambient pollution averages calculated for different alternative energy futures. Thus, we have assumed that decay-rate effects can be neglected for SO_2.

The Wisconsin SCA Dispersion Parameters

Based on the above assumptions, a set of SCA dispersion parameters for SO_2 pollution was developed for Wisconsin conditions. The resulting set of Wisconsin SCA dispersion parameters is shown in Table 1.

Table 1: Wisconsin SCA Dispersion Parameters for SO_2 Pollution

$D_1 = 20 \cdot 10^{-4} \mu g/m^3$ per ton emitted

$D_2 = 4.2 \cdot 10^{-4} \mu g/m^3$ per ton emitted

$D_3 = 0.30 \cdot 10^{-4} \mu g/m^3$ per ton emitted

$F(E_t) = (E_1 + E_2 + 0.1E_3)$ at year t

The area source SCA dispersion parameter was based on the results of the University of Wisconsin Air Quality Modelling Group's three-dimensional box dispersion model [25]. Calculations were provided of the ground-level SO_2 concentrations due to residential and commercial coal use in Milwaukee for 1970-71 and 1973-74. The area of these sources was much less than the total Milwaukee urban area, but the distribution of sources mirrored a typical urban region. This typical distribution of sources was defined as the model urban area of ground-level sources of pollution to be used in this work. The radius of the model urban area was approximately 10 km and the arithmetic average of the ground-level concentrations over this radius was taken to develop the SCA dispersion parameter.

The point source SCA dispersion parameters were calculated using the multiple-point source Gaussian plume model. The Moses and Carson plume-rise formula [26] was used because it represents well the type and size of point sources for Wisconsin. The meteorological statistics for the city of Madison were used since Madison is located in the southern part of the state where the majority of impacts occur. The SCA dispersion parameter for medium-level point sources was calculated using 24 point sources that, as a group, reflected the stack characteristics of the mix of industrial point sources in southeastern Wisconsin, the state's most industrialized area. The calculations were averaged over a 30 km by 30 km grid. The SCA dispersion parameter for high-level point sources was calculated by adding to the industrial sources an average electricity generation station with a stack height of 170 m.

The constants a, b, and c of the emission strength function, F(E), were calculated using the same set of calculations as for the SCA dispersion parameters. In this case, an annular section was taken that extended 30-40 km from the sources. Thus the Wisconsin emission strength function represents the relative contribution of the different classes of urban area emissions to the urban area's surrounding background concentration at the near and medium range; the Wisconsin emission strength function, F(E) does not give the relative contribution of the different classes of urban area emissions to the background concentration for long-range pollution transport, i.e. several hundred kilometers.

Validation

Validation of the SCA method is still in the initial stages. It requires detailed emission inventories for urban areas as well as detailed dispersion model calculations[2] based on these emission inventories. Also, the emission inventories and model calculations need to be broken down into the three classes of emission sources mentioned in Section II.

Comparison of the results of the Wisconsin SCA model with monitoring data and with detailed dispersion model results for Wisconsin cities form the first step in the validation of the SCA method. The comparison must be made for cities with a radius greater than 5 km because the urban size effect is not included in the area source SCA dispersion parameter. Two Wisconsin cities, Madison and Milwaukee, are large enough and have the required emission inventories and detailed dispersion model calculations to begin a validation analysis.

When comparing SCA model results with results of detailed dispersion models averaged over the urban area, one would expect the agreement between the calculated urban average ground-level concentrations to be reasonably close. When comparing SCA model results with monitoring data that have been a averaged for the urban area, however, one would expect the monitoring results to be consistently higher, up to factors of 2-5. This is because monitoring stations are usually located in the central part of an urban area where concentrations are highest and individual stations can be strongly influenced by particular point sources. Thus monitoring data are not necessarily representative of the ambient pollution concentration over the entire urban region.

Two pollutants, SO_2 and particulate matter (PM), were selected for the validation analysis of the SCA model. The SCA dispersion parameters were developed for SO_2 pollution and the

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[2] Detailed dispersion model calculations as carried out for Wisconsin consist of multiple-point source Gaussian plume model calculations and three-dimensional box model calculations for area sources.

SO_2 validation analysis is the central concern. However, a PM validation analysis is included to provide an initial test of the transferability of the SCA method to other non-reacting pollutants.

Both SO_2 and PM have had the longest history as recognized pollutants, being the major components of "classical smog". Interest in these two pollutants is strong. Air pollution standards in terms of annual average concentrations exist for both pollutants in most countries that have standards, and they are the most widely monitored of all the pollutants. Therefore, the best monitoring data base and the most complete detailed dispersion model calculations of annual-average concentrations exist for these two pollutants. In addition, unlike hydrocarbons or carbon monoxide, strong sources of SO_2 and PM are found in each of the three emission classes defined in the SCA method. This facilitates a better and more complete validation analysis.

Comparison of SO_2 Pollution Levels: Milwaukee

Detailed dispersion model calculations for Milwaukee have been performed for 1973 [27]. When the monitoring data are compared with the model results for the monitoring sites, the statistical correlation coefficient between the model calculations and the monitoring data is $r = 0.91$.

Isopleths of SO_2 concentrations attributable to area sources and point sources were available from the detailed dispersion model calculations for the Milwaukee urban area. These isopleths were averaged over the Milwaukee urban area for the comparisons with the SCA model.

The same emission inventory data that formed the data base for the detailed dispersion model was used for the SCA model calculations. The total emissions by type are shown in Table 2. For the SCA model results the transportation, residential and commercial emissions were multiplied by SCA dispersion parameter, D_1, the industrial emissions by D_2 and the power plant emissions by

Table 2: Milwaukee, SO_2 Comparison
1973

	Emissions* (tons)	SCA Model Results ($\mu g/m^3$)		Detailed Dispersion Model Results** ($\mu g/m^3$)	Monitoring Data* ($\mu g/m^3$)
Area Sources					
Transportation	743	1.49	18.70	17.3	
Residential & Commercial	8,605	17.21			
Point Sources					
Industry	7,486	3.14	7.33	6.7	
Power Plants	139,800	4.19			
Subtotal			26.03	24.0	
Background			5.00	5.0	
TOTAL			31.03	29.0	35-40

*Source: Ref. [28]

**Source: Ref. [27]

D_3. These results and the comparison with the detailed dispersion model results and monitoring data for the Milwaukee area are also given in Table 2. The comparison between the model results is excellent. As expected, the average of the monitoring data is higher than either model's urban area average.

Although Milwaukee area data were used to develop the Wisconsin SCA dispersion parameters, the Milwaukee comparison is not a redundant or circular one. The emissions data base for the SCA dispersion parameter development was different from the Milwaukee area emissions data base used to calculate the 1973 Milwaukee SO_2 concentrations. The model urban area for the D_1 SCA parameter calibration had only central Milwaukee coal emissions, which totaled 2,230 tons of SO_2 emitted. This compares with 9,348 tons of SO_2 for the total Milwaukee area. The point source SCA parameter calibration used a representative sample of twenty-five point sources which had a total emission of 1,380 tons of SO_2 for the industrial sources and 43,100 tons of SO_2 for the single power plant. This compares with 7,486 tons of SO_2 from one hundred seventy-five industrial sources and 139,800 tons of SO_2 from seven power plants for the total Milwaukee area. The detailed dispersion model calculations for each case were completely independent; and the radius of the model-area was 10 km, whereas the radius of the Milwaukee urban area is sixteen kilometers.

Comparison of SO_2 Pollution Levels: Madison

Detailed emission inventory data and detailed dispersion model calculations are available for Madison for 1971 [18, 29]. In this case the statistical coefficient of correlations between the monitoring station measurements and the concentrations calculated by the model for the monitoring stations sites is $r = 0.84$. Unfortunately, the detailed dispersion model results for the annual-average pollution concentrations are only available for the same locations in Madison as the monitoring stations. Therefore, the SO_2 validation for Madison must proceed in a different manner.

All of the monitoring sites in Madison are in the city center, the area of highest air pollution concentrations. The question is, how much higher is the urban center average concentration compared to the average concentration for the entire urban area. To answer this question, a multiplicative factor must be derived using the SCA method that will take the average concentrations predicted for the entire urban area and scale them up to an urban center average. The resulting SCA concentrations predicted for the urban center are the concentrations that should be compared with the detailed dispersion model results and the monitoring data for Madison.

It is possible to go back to the data of the model urban area used to develop the SCA dispersion parameters and take an arithmetic average of the air pollution concentrations that represents only the urban center (and the highest concentrations). The ratio of this urban center average to the urban area average multiplied by the SCA dispersion parameter for the entire urban area will give a new SCA urban center disperion parameter D_i'. The urban area and urban center averages are schematically shown in Figure 5. To correspond with Madison, the urban center area is 10% of the total urban area.

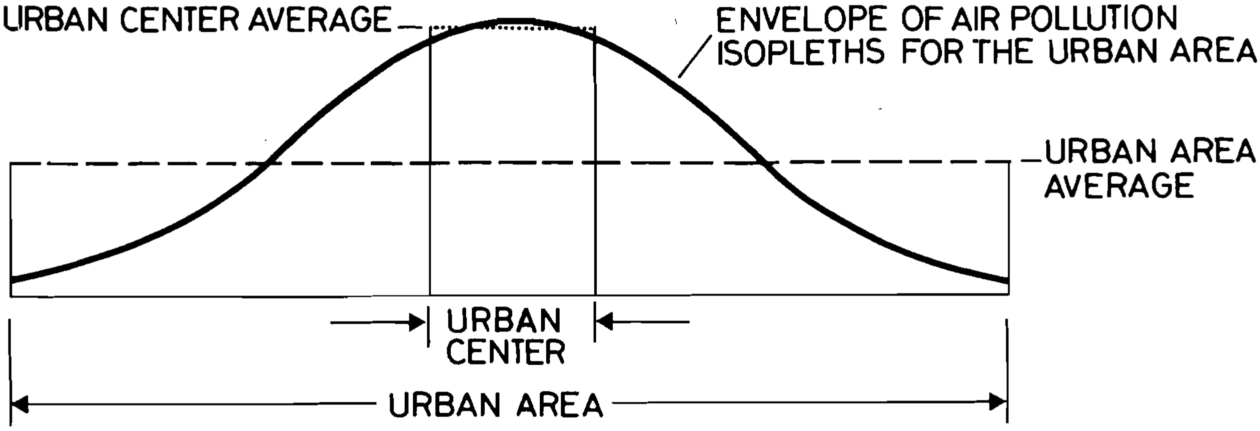

Figure 5: Schematic Urban Cross-Section of Air Pollution Concentration with Urban Area and Urban Center Average Concentrations.

The D_i''s that were calculated for the Madison case are:

$D_1' = 3.92D_1$

$D_2' = 3.58D_2$

$D_3' = 1.1D_3$

For Madison it is not necessary to calculate D_3' because Madison's power plant has a stack height corresponding to the industrial sources. However, for completeness, D_3' was included here.

The Madison SO_2 emissions and SO_2 comparisons are shown in Table 3. The transportation, residential and commercial emissions were multiplied by D_1' and the industrial and power plant emissions were multiplied by D_2'. The regular SCA model results are included in the comparison for reference sake. The urban center SCA prediction is in very good agreement with the detailed dispersion model results. The agreement for the individual emission classes, i.e. the area sources and point sources, is not as good as for Milwaukee, but the agreement for the total SO_2 concentration is

Table 3: Madison, SO_2 Comparison
1971

	Emissions* (tons)	SCA Model Results ($\mu g/m^3$)	Urban Center SCA Model Results ($\mu g/m^3$)	Detailed Dispersion Model Results** ($\mu g/m^3$)
Area Sources				
Transportation	227	.45 } 2.74	10.74	13.74
Residential & Commercial	1,141	2.28		
Point Sources				
Industry	6,638	2.79 } 6.12	21.91	20.36
Power Plant	7,931	3.33		
Subtotal		8.86	32.65	34.1
Background		2.00	2.00	2.0
TOTAL		10.86	34.65	36.1

*Source: Ref [29].

**Source: Ref. [18]

better for Madison than for Milwaukee: Ninety-six percent of the detailed dispersion model total to 107% of the total, respectively.

The agreement for both Milwaukee and Madison is good for SO_2 pollution. The agreement is more meaningful because the two urban areas are greatly different, both in size (187,000 inhabitants for Madison and 944,500 inhabitants for Milwaukee) and in the structure of their emissions. Milwaukee has a large fraction of its SO_2 emissions coming from power plants and the industrial emissions are approximately the same magnitude as the residential and commercial emissions. Madison has a power plant whose stacks are like industrial stacks and its industrial and power plant SO_2 emissions dominate the area source emissions. Even with these great differences between the urban areas, the agreement between the SCA model and the detailed dispersion model results is (individually) good for both the area sources and the combined point sources for each urban area. For SO_2 air pollution the model prescribed by the SCA method seems to provide a reasonable picture of the overall ground-level pollution concentrations. The SCA model also appears to provide a good picture of the relative contribution each emission class makes to the ground-level pollution concentration.

Comparison of PM Levels: Milwaukee

The data for the Milwaukee particulate matter comparison comes from the same set of 1973 base year dispersion model calculations and emissions inventory data as for the SO_2 comparison. Milwaukee isopleth charts for PM were available for more emission source classifications than were available for SO_2. The PM comparison for 1973 is shown in Table 4. Again transportation, residential and commercial emissions were multiplied by D_1, industrial emissions by D_2 and power plant emissions by D_3.

Table 4: Milwaukee, Particulate Matter Comparison, 1973

	Emissions* (tons)	SCA Model Results ($\mu g/m^3$)		Detailed Dispersion Model Results** ($\mu g/m^3$)		Monitoring Data** ($\mu g/m^3$)
Area Sources						
Transportation	2,368	4.74	7.95	5.4	10.8	
Residential, Commercial & Other	1,604	3.21		5.4		
Point Sources						
Industry	8,459	3.55	3.8		6.1	
Power Plants	7,960	0.24				
Subtotal			11.75		16.9	
Background			45.00		45.00	
TOTAL			56.75		61.9	73.05

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[*] Source of Emissions: Ref. [28]

[**] Source: Ref. [27].

The agreement between the SCA model results and the detailed dispersion model results is poor. In every emissions category the SCA model prediction is significantly lower than the detailed dispersion model prediction. This will be discussed after making the Madison PM comparison. The monitoring data are higher than the total from either model. However, when the calculations of the detailed dispersion model are taken at the same points as the monitoring sites, the resulting average PM concentration calculated by the model becomes 70.8 μg/m^3. This is in good agreement with the monitoring data.

Comparison of PM Pollution Levels: Madison

The same set of 1971 Madison data provides the basis for the particulate matter comparisons. The same procedure must be used as in the SO_2 comparison because the detailed dispersion model calculations for PM are also only available for the monitoring sites. Thus the same D_i''s can be used that were used for the SO_2 comparison. The emissions and model results are shown in Table 5 for the Madison PM comparison.

Table 5: Madison, Particulate Matter Comparison, 1971

	Emissions* (tons)	SCA Model Results (μg/m^3)	Urban Center SCA Model Results (μg/m^3)	Detailed Dispersion Model Results** (μg/m^3)	Monitoring Data** (μg/m^3)
Area Sources					
Transportation	1,226	2.45 } 5.70	22.35	23.9	
Residential, Commercial & Other	1,625	3.25			
Point Sources					
Industry	1,116	0.47 } 2.19	7.83	5.5	
Power Plants	4,094	1.72			
Subtotal		7.89	30.18	29.4	
Background		30.00	30.00	30.0	
TOTAL		37.89	60.18	59.4	75

*Source: Ref. [29]

**Source: Ref. [18]

The agreement between the urban center SCA prediction and the detailed dispersion results for Madison is excellent for the total PM concentration. As in the Madison SO_2 comparison, the SCA model gives higher concentrations for the point source emissions and lower concentrations for the area source emissions than given by the detailed dispersion model calculations. It is felt that the difference between the detailed dispersion model results and the monitoring data represents deficiencies in the PM emissions inventory [28]. Emission inventory deficiencies do not effect the SCA dispersion parameter calibrations, only the predicted ground-level concentrations.

It is unclear why the agreement for Madison is good for both SO_2 and PM but for Milwaukee it is good only for SC_2. As a first check, the same procedure that was used to calculate the Madison urban center concentration can be applied to Milwaukee for PM concentrations. The results of that check are shown in Table 6. The agreement is excellent for the totals. The agreement for the individual emission classes is not so good.

Table 6: Milwaukee Urban Center PM Comparison

	Milwaukee Urban Center SCA Model Results (μg/m^3)	Milwaukee Urban Center Monitoring Results* (μg/m^3)	Urban Center Detailed Dispersion Model Results* For Monitoring Sites (μg/m^3)	Urban Center Detailed Dispersion Model Results Isopleth Charts (μg/m^3)
Area Sources				
Transportation	18.6		10.7	15.5
Residential, Commercial & Others	12.6		13.7	10.5
Point Sources				
Industry	12.7 13.0		20.0	24.5
Power Plant	0.3			
Subtotal	44.2		44.4	50.5
Background	45.0		45.0	45.0
TOTAL	99.2	100.3	99.4	105.5

*Source: Ref. [27]

For the area sources, the agreement is best, and the differences that do exist are understandable. For the residential, commercial and other PM emission sources, the isopleth chart of PM concentrations for Milwaukee indicates an urban size saturation effect and the maximum concentration is spread very broadly over 20% of the total urban area. Moreover, the absolute PM maximum is not large relative to the total urban area average PM concentration for these emission sources -- a factor of two. (In transportation emissions the urban center PM concentration is about a factor of three higher than the urban average PM concentration.) The data used to develop the SCA dispersion parameter for area sources do not show the saturation effect shown in the Milwaukee residential and commercial PM concentration data. The area of maximum concentration in this data is only 5% of the total model urban area and the peak SO_2 concentration is much larger than the urban area average SO_2 concentration -- nearly a factor of 4. (The factor of 3.92 used to calculate D_1'). Thus it is expected that the SCA method, in the Milwaukee case, would over-estimate the urban center peak relative to the total urban average for the PM area source emission class. This implies that the SCA estimate of the urban average PM concentration is low for large urban areas where the area source emissions are more evenly spread throughout the urban area, rather than being more concentrated in the center.

This effect of spreading would explain why the SCA model results are low for PM. However, the area source SCA model results for Milwaukee SO_2 are higher than the detailed dispersion model urban average, although the agreement is close. This contradicts the explanation for the PM results. The implication is that the emission sources are sufficiently different for SO_2 and PM, that the urban size saturation effect does not play as strong a role for SO_2. This is quite reasonable, because it is known that most of the SO_2 emissions come from old coal-burning establishments in the center of Milwaukee.

Since we stated earlier that we have ignored the urban size effect for the present, the SCA model results for the Milwaukee PM area source class of emissions would be expected to be lower than the detailed dispersion model results. The SCA model results for SO_2 area sources would not be expected to be lower than the detailed dispersion model results. The apparent contradiction between PM and SO_2 SCA results seems to have a resolution for area sources. Thus the initial validation analysis for area sources indicates that the SCA method works well and works best for SO_2.

The situation for point source emissions is not as clear as for area sources. The disagreement between the SCA model results and the detailed dispersion model results are in the same direction as for PM. But the disparity is worse. The same apparent contradiction between the SO_2 results and the PM results is also present. But again the disparity is worse. The difference in the source configuration between SO_2 and PM sources may again be playing a major role, because big SO_2 emitters are not necessarily big PM emitters. The fact that the power plants play a dominant role in the SO_2 point source urban average and not for PM urban averages may also play a role in the Milwaukee validation cases. More detailed investigations must be carried out before the disparity of the point source SCA model results for the PM can be clearly explained. Thus the initial validation analysis for point sources indicates that the SCA method seems to work well for SO_2 pollution and not so well for PM pollution.

Conclusions of the Validation Effort

There are three conclusions that can be derived from the comparisons for SO_2 and PM for Wisconsin:

1) The SCA model prescribed by the SCA method seems to provide a reasonable picture of the overall ambient pollution concentration in an urban area. It appears to provide a good picture of the relative contribution to ambient ground-level pollution concentrations from different emission classes. When necessary, the SCA method also appears to provide a reasonable picture of

urban center pollution concentrations relative to the entire urban area average. The comparisons of the Wisconsin SCA model with detailed dispersion results and monitoring data for Wisconsin form an initial basis for validation of the method, and they are as good as might be expected. We believe, therefore, that the method would also do well in other regions for policy evaluation. The SCA dispersion parameters can be modified to reflect the differences in the meteorology in different regions.

2) The SCA model is able to represent the degree of SO_2 pollution in urban areas. Further, the SCA model is able to provide guidance for distinguishing the sources of the SO_2 ground-level pollution concentrations. Responsibility for these SO_2 concentrations can be assigned to the three emission classes. If damage functions are known, those quantifiable parts of environmental impacts attributable to SO_2 air pollution can be calculated using the ground-level air pollution concentrations provided by the SCA model.

3) Conclusion 2) above for SO_2 does not hold in toto for particulate matter. The SCA model cannot be used for PM with the degree of confidence that it can be used for SO_2. But the SCA model together with PM emissions still provides better guidance for PM pollution impacts than emissions would alone.

APPLICATION OF THE APPROXIMATION METHOD TO SPECIFIC CASE STUDIES

As stated earlier, the major objective of the SCA method is to develop a flexible and simple means for addressing policy questions concerned with alternative futures that include air pollution impacts related to energy use. It has been demonstrated above that the SCA method can meet this objective. It is worth discussing now the results of the application of the method to specific case studies.

The first application of the SCA method was carried out at IIASA within the research program on Management of Regional Energy/ Environment Systems [30,31]. This involved three regional case studies, namely, the German Democratic Republic (GDR), the Rhone-Alpes region of France, and the state of Wisconsin in the USA. The SCA models are described for two cities, one in Wisconsin and one in the GDR. These two cities demonstrate the difference in how air pollution impact is credited to an emission class when only emissions are considered and when dispersion is considered. Two sensitivity studies are presented to illustrate the use of the SCA method to provide insights into questions raised at the regional level concerning energy use and air pollution impact.

Three-Region Study Results

In the Three-Region Study alternative scenarios were written for each region and from these scenarios the energy demand was calculated for each economic sector, i.e. the industrial, residential, transportation and commercial sectors. This energy demand was converted into SO_2 emissions and these emissions were associated with the appropriate urban center. An SCA model then converted the emissions into ground level SO_2 concentration (or SO_2 dose) for the urban areas. Results are shown for a GDR urban area and a Wisconsin urban area in Figure 6 in terms of the percentage of emissions in each emission source class and in terms of the percentage of the dose that is attributable to each emission source class. This Figure and Tables 2-5 demonstrate that emissions alone are a poor indicator of air pollution impacts at the ground level. The SCA method is also useful following this emission change over time and in indicating how the relative responsibility for the ground-level concentration changes; for example, if the Wisconsin urban area emissions evolve over time to the emission structure of the GDR urban area. Removing the GDR urban area district heat, the Wisconsin urban area emissions did

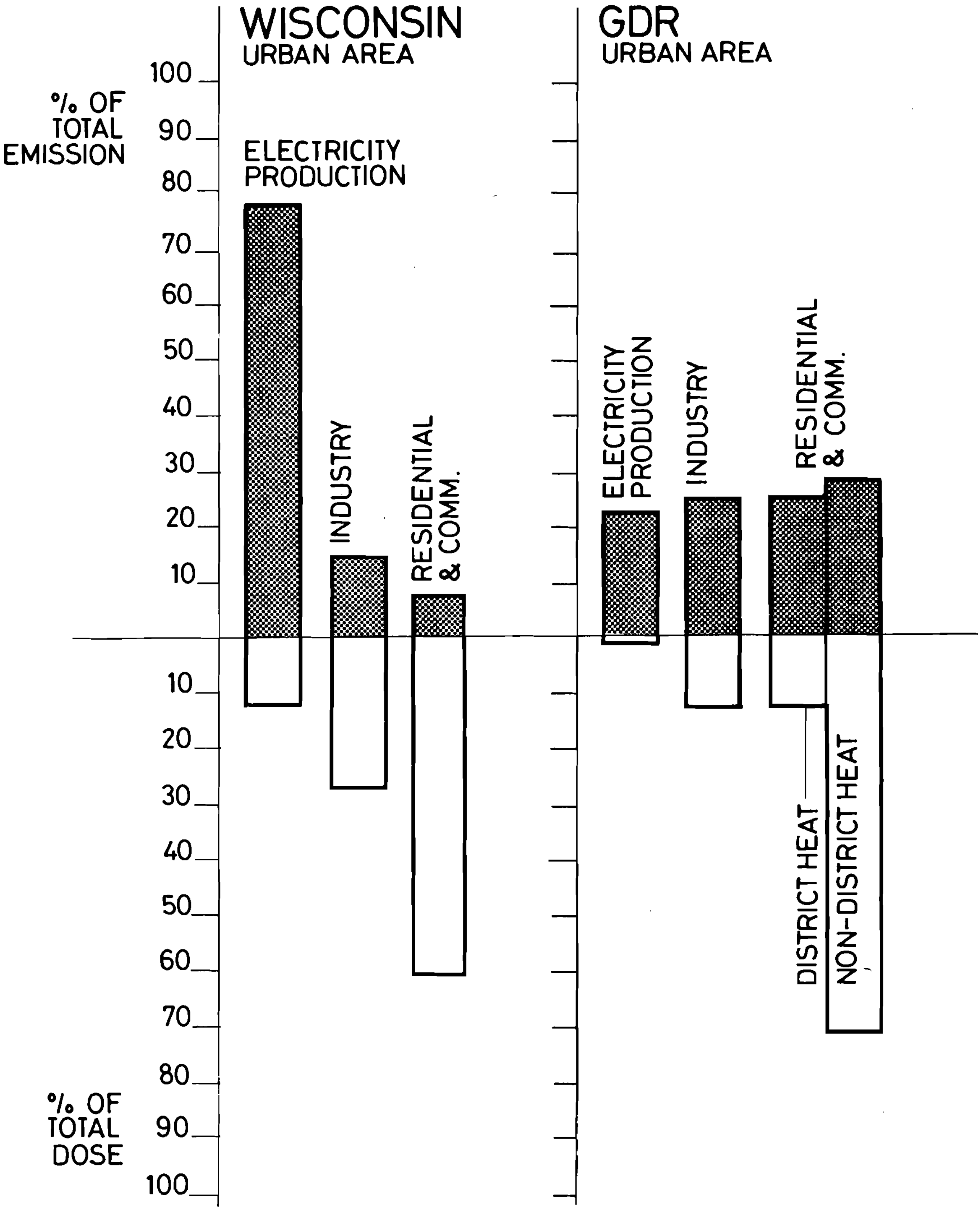

Figure 6: SO_2 Emissions and Ground-Level Concentrations, 1970

evolve in one of the Wisconsin scenarios to an emissions structure similar to that of the GDR urban area. This was because the service sector grew more rapidly than the industrial sector (historical trend) and because the electric power stations put on SO_2 emissions controls to meet the US Environmental Protection Agency Standards. The ability to track such emission changes and convert them to ground-level concentrations illustrates the value of the SCA method for scenario and environmental impact analysis.

For the GDR urban area it is interesting to note that district heating satisfies a significant amount of the residential and commercial space heat demand. District heating stations have tall stacks; therefore, their emissions are multiplied by D_2, the medium-height point source SCA dispersion parameter. For the same amount of space heating emissions, less air pollution impact occurs at the local level with the use of district heat. This will be presented in more detail in the following sensitivity study.

Sensitivity Studies

Emission Source

One issue of great interest to the GDR was the use of district heating to ameliorate the SO_2 environmental impact in its urban areas. The GDR has large coal reserves and desires to use the coal rather than import petroleum or natural gas. But the direct use of coal in the homes for space heat creates a significant SO_2 pollution problem. District heating is already practiced to a large degree in the GDR and is a feasible alternative to the individual home furnace for the supply of space heat.

Residential space heating SO_2 emissions as a function of time are shown in Figure 7. for a representative medium-sized

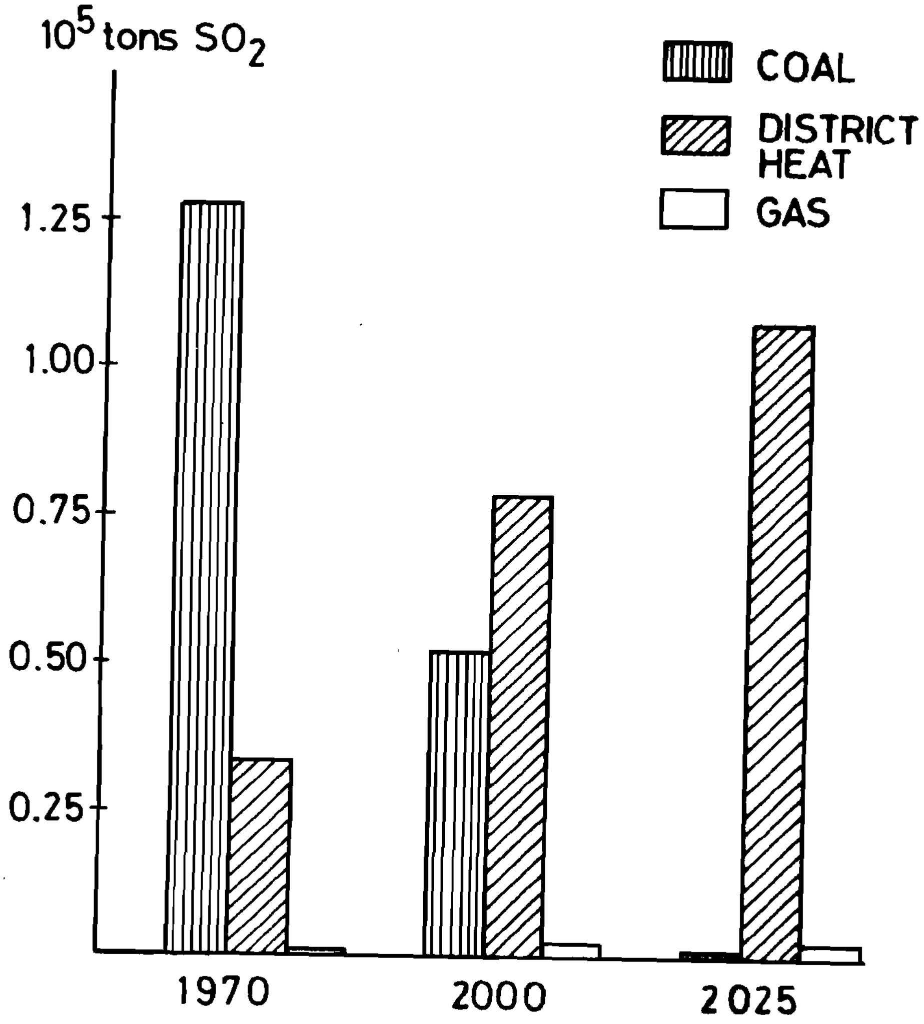

Figure 7: Main city residential SO_2 emissions by source, GDR urban area.

urban area in the southern GDR. The phasing out of direct coal use and its replacement by coal generated district heat for residential space heating could be nearly accomplished by 2025 for a scenario projecting maximum possible growth of district heat without retrofit and with little substitution by other fuels. This phase-out and replacement is illustrated by the change in the

SO_2 emission source in Figure 7.

Figure 8 shows the consequences of such a shift to district heat on the SO_2 ground level concentrations. The total SO_2 emissions decline somewhat because some SO_2 control is assumed to be applied at the district heating plants. But the ambient ground-level SO_2 concentration from space heating decreases dramatically.

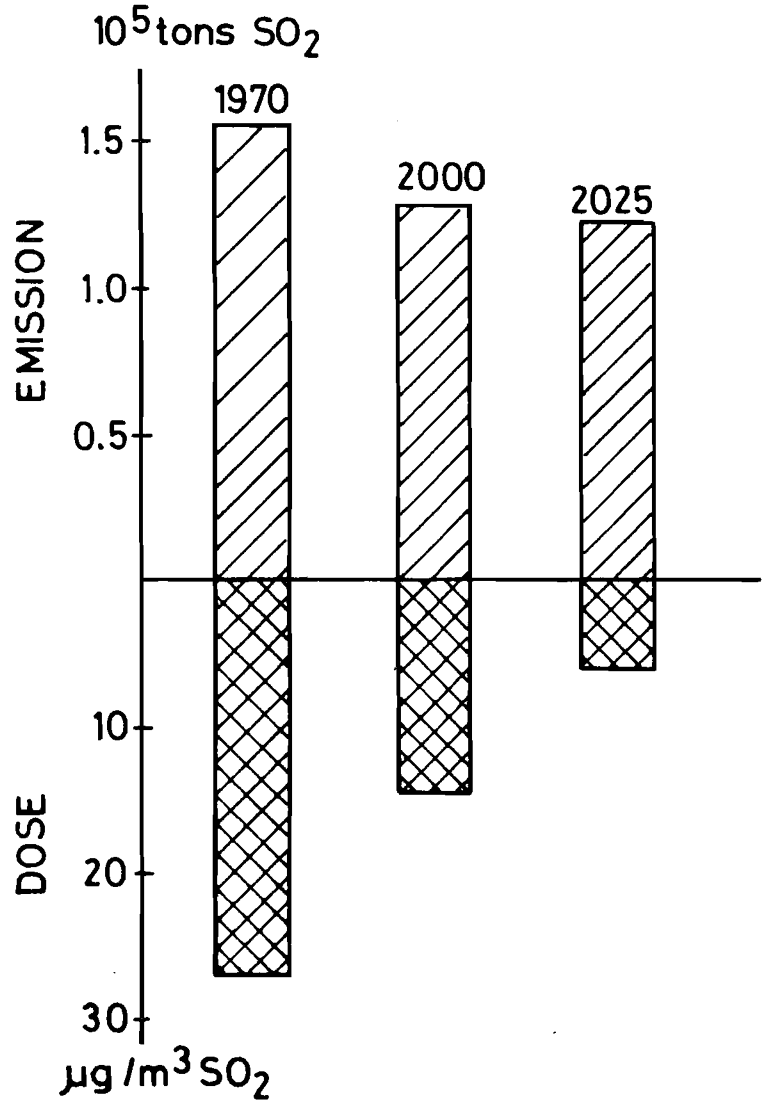

Figure 8: Main city residential emissions versus dose for SO_2, GDR urban area.

As mentioned earlier, the decrease in the urban SO_2 ground-level concentrations projected by the SCA model is due to a transfer of the emissions from emission source class 1 (area sources) to emission source class 2 (medium-height point sources). Thus the environmental impact is expected to greatly decrease in the urban area for approximately the same coal use. One must be careful, however, in applying this conclusion everywhere, because it does not hold outside the urban area. Outside the urban area, the relative contribution of emissions to the ground-level concentrations is the same for emission source classes 1 and 2. This is seen in the emission strength function,[F(E),Table 1], since the constants a and b are both equal to 1.

Stack Height

In some regions, the response to air pollution standards has been to increase the stack height of the power plants rather than put in SO_2 pollution controls. How effective such a policy might be can be investigated by the SCA method. This can be accomplished by calculating the SCA dispersion parameter D_3 for different stack heights. Figure 9 shows the estimated SCA dispersion parameter D_3 as a function of stack height for a given power plant with given emissions. The stack heights ranged from 80 - 300m. A dramatic decrease in the SCA dispersion

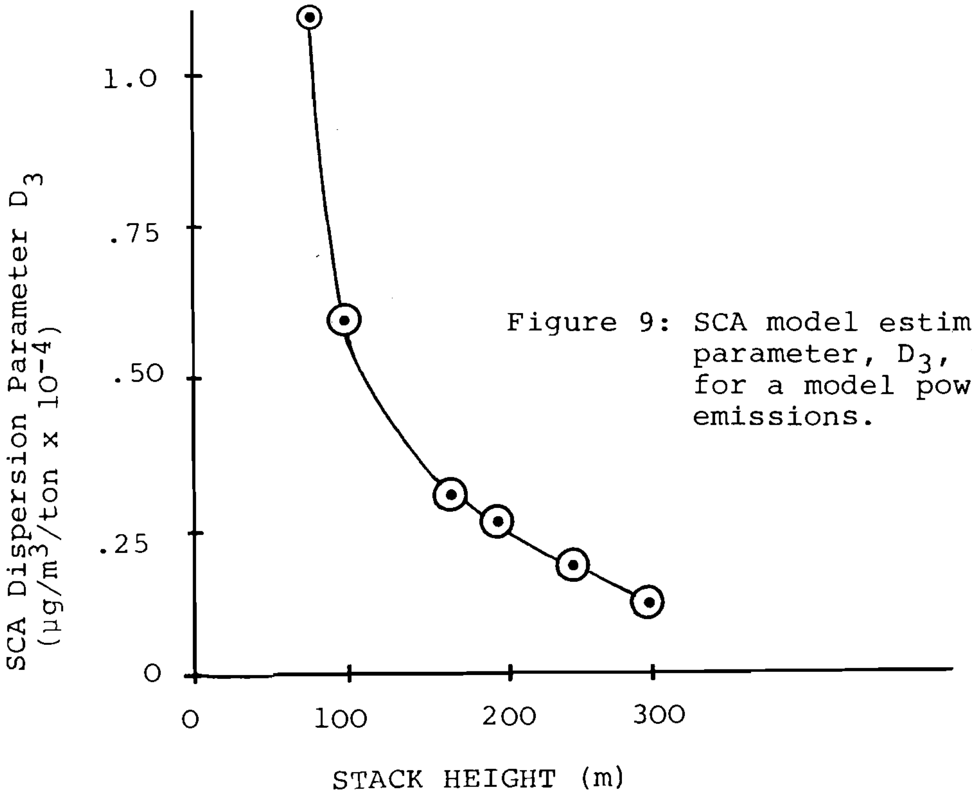

Figure 9: SCA model estimated dispersion parameter, D_3, versus stack height for a model power plant with given emissions.

parameter's value occurs as the stack height is increased to 150 m; thereafter, the rate of decrease of D_3 slows down considerably. It must again be emphasized that this SCA dispersion parameter applies only to the urban area.

CONCLUSIONS

A Smeared Concentration Approximation (SCA) method was developed to include the dispersion of air pollution emissions in the analysis of regional air pollution impacts. One of the major objectives of the SCA method is to provide a flexible and simple means for calculating ground-level pollution concentrations for alternative energy futures (energy scenarios) for use in the analysis of air pollution impacts.

The SCA method was described and its critical assumptions were outlined. The primary emphasis was on SO_2 pollution. An SCA model was developed as prescribed by the SCA method; in particular the Wisconsin SCA model was given. A preliminary validation of the Wisconsin SCA model was made for two pollutants -- SO_2 and particulate matter.

The results of this initial validation indicate that the SCA method seems to provide a reasonable picture of the overall ambient air pollution concentration in an urban area. The SCA method also appears to provide a good picture of the relative contribution each emission class makes to the ground-level concentration. The preliminary validation was good for SO_2, but weaker for PM. The preliminary validation was good enough that we believe the SCA method is usable in other regions for long-term policy analysis in those regions. However, the model must be validated in other regions before general applicability can be claimed.

Results of the use of the SCA method in specific case studies indicate the value the method has for addressing air pollution issues and air pollution impacts. The validation exercise also contained within it the demonstration that dispersion is important and that decisions should not be made only on the basis of emissions.

References

[1] Foell, W.K., J.W. Mitchell, J.L. Pappas, *The WIsconsin Regional Energy Model: A Systems Approach*, Report 56, Institute for Environmental Studies, Univ. of Wisconsin Energy Systems Research Group, Madison, Wisconsin.

[2] Buehring, W.A. and W.K. Foell, *Environmental Impacts of Electrical Generation: A System-Wide Approach*, RR-76-13, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

[3] Buehring, W.A., R.L. Dennis and A. Hölzl, *Evaluation of Health Effects from Sulfur Dioxide Emissions for a Reference Coal-Fired Power Plant*, RM-76-23, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

[4] Foell, W.K., *Scenario Writing: One Component of a Systems Approach to Energy/Environment Management*, RM-76-20, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

[5] Southeastern Wisconsin Regional Planning Commission, *Regional Air Quality Maintenance Planning Program Prospectus*, Waukesha, Wisconsin, July 1974.

[6] Knox, J.B., Numerical Modelling of Transport Diffusion and Deposition of Pollutants for Regions and Extended Scales, *Journal of the Air Pollution Control Association*, *24*, 7, (July 1974), 660-664.

[7] Shir, C.C. and L.J. Shieh, A Generalized Urban Air Pollution Model and Its Application to the Study of SO_2 Distributions in the St. Louis Metropolitan Area, *Journal of Applied Meteorology*, *13*,2 (March 1974), 185-204.

[8] Lamb, R.G., A.V. Levy and J. Burkle, *The Calculation of Long Period Mean Pollutant Concentrations in an Urban Atmosphere. Part II: Simulation of Annual Sulfur Dioxide Concentrations in Mexico City*, Technical Report CCAL-75-17, Centro Cientifico de America Latina, 1975.

[9] Seinfeld, J.H., S.D. Reynolds and P.M. Roth, Simulation of Urban Air Pollution, *Advances in Chemistry*, *113*, (1972), 58.

[10] Keddie, A.W.C., G.H. Roberts and F.P. Williams, The Application of Numerical Modelling to Air Pollution in the Forth Valley, in C.A. Brebbia, ed., *Mathematical Models for Environmental Problems*, Pentsch Press Ltd, (1976).

[11] Finklea, J.F., et al., *Health Effects of Increasing Sulfur Oxide Emissions*, Draft Report, National Environmental Research, USEPA, North Carolina, 1975.

[12] Larsen, R.I., An Air Quality Data Analysis System for Interrelating Effects, Standards, and Needed Source Reductions - Part 2., *Journal of the Air Pollution Control Association*, *24*, 6, (1974), 551-558.

Larsen, R.I., *A Mathematical Model for Relating Air Quality Measurements to Air Quality Standards*, *USEPA, AP-89* (Nov. 1971).

[13] Stearn, A.C., *Air Pollution*, Vol. I, Academic Press, New York, 1968.

[14] Reiquam, H., An Atmospheric Transport and Accumulation Model for Airsheds, *Atmospheric Environment*, *4*, (1970), 233-247.

[15] Turner, D.B., *Workbook of Atmospheric Dispersion Estimates*, United States Environmental Protection Agency, AP-26, (1970).

[16] Carpenter, et al., Principal Plume Dispersion Models: TVA Power Plants, *Journal of Air Pollution Control Assoc*., *21* (8), (1971), 491-495.

[17] Ragland, K.W., R.L. Dennis, Point Source Atmospheric Diffusion Model with Variable Wind and Diffusivity Profiles, *Atmospheric Environment*, *9*, (1975), 175-189.

[18] Ragland, K.W., R.L. Dennis, and K.E. Wilkening, Boundary-Layer Model for Transport of Urban Air Pollutants. (Published in the Proceedings of the March 18, 1975 National AIChE Meeting - 1976).

[19] Shir, C.C. and L.J. Shieh, *Development of An Urban Air Quality Simulation Model with Compatible RAPS Data*, Vol. I and II, USEPA-600/4-75-005-6 (May 1975).

[20] Martin, D.O., An Urban Diffusion Model for Estimating Long-Term Average Values of Air Quality, *Journal of Air Pollution Control Assoc*., *21*, (1971), 16-19.

[21] Faude, D., et al., *Energie und Umwelt in Baden-Wuerttemberg* Gesellschaft fuer Kernforschung M.B.H., Karlsruhe, BRD, April 1974.

[22] Ragland, K.W., Multiple Box Model for Dispersion of Air Pollutants from Area Sources, *Atmospheric Environment*, *7*, (1973), 1017-1032.

[23] Tobler, W.R., City Sizes, Morphology and Interaction, IIASA Internal Paper.

[24] Eliassen, A., J. Saltbones, Decay and Transformation Rates of SO2, As Estimated from Emission Data, Trajectories and Measured Air Concentrations, *Atmos. Environ*., *9*, (4), (1975), 425-429.

[25] Wilkening, K.E., Sulfur Dioxide and Particulate Matter Concentrations Due to Residential, Commercial and School Coal Usage in Milwaukee County, A Report of the Air Quality Modelling Group, University of Wisconsin, Prepared for the Wisconsin Department of Natural Resources (July 1975).

[26] Moses, H. and M.R. Kraimer, Plume Rise Determination - A New Technique without Equations, Journal of the Air Pollution Control Association, 22, (8), (1972), 621-630.

[27] Ragland, K.W., K.E. Wilkening and T.A. Kaufmann, Air Quality Simulation and Analysis for the Base Year, Staff Memorandum Prepared for the Regional Air Quality Maintenance Planning Program, March 1, 1976.

[28] Ragland, K.W., Private Communication.

[29] Ragland, K.W., and M.J. Miller, Air Pollution Emissions Inventory in the Madison, Wisconsin Area, Institute for Environmental Studies Working Paper 5, University of Wisconsin, Madison (October 1972).

[30] Foell, W.K., The IIASA Research Program on Management of Regional Energy/Environment Systems, RM-76-40, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

[31] Foell, W.K., ed., Proceedings of the IIASA Workshop on Integrated Management of Regional Energy/Environment Systems: November 10-14, 1975, International Institute for Applied Systems Analysis, Laxenburg, Austria (in Press).

APPENDIX

PAPERS IN THE IIASA PUBLICATION SERIES ON MANAGEMENT OF ENERGY/ ENVIRONMENT SYSTEMS

Keeney, R.L., Energy Policy and Value Tradeoffs, RM-75-76, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1975.

Foell, W.K., Scenario Writing: One Component of a Systems Approach to Energy/Environment Management, RM-76-20, International Institute for Applied Systems Analysis, Laxenburg, Austria,1976.

Born, S., C. Cicchetti, R. Cudahy, J. Pappas, P. Hedrich, K. Lindner, D. Ufer, J.-M. Martin, D. Finon, Energy/ Environment Models and their Relationships to Planning in Wisconsin, the German Democratic Republic, and Rhone-Alpes, RM-76-21, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

Foell, W.K., The IIASA Research Program on Management of Regional Energy/Environment Systems, RM-76-40, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

Buehring, W.A., W.K. Foell, Environmental Impact of Electrical Generation: A Systemwide Approach, RR-76-13, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

Buehring, W.A., W.K. Foell, R.L. Keeney, Energy/Environment Management: Application of Decision Analysis, RR-76-14, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

Stehfest, H., A Methodology for Regional Energy Supply Optimization, RM-76-57, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

Buehring, W.A., R.L. Dennis, A. Hölzl, Evaluation of Health Effects from Sulfur Dioxide Emissions for a Reference Coal-Fired Power Plant, RM-76-23, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

Buehring, J.S., WISSIM: An Interactive Computer Simulation Control Language, RM-76-24, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

Dennis, R.L., Regional Air Pollution Impact: A Dispersion Methodology Developed and Applied to Energy Systems, RM-76-22, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1976.

Prucknicki, J., Air Pollution Dispersion Models as Used in Poland in Regional Development Planning, RM-77-5, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1977.