THE SMEARED CONCENTRATION APPROXIMATION METHOD: A SIMPLIFIED AIR POLLUTION DISPERSION METHODOLOGY FOR REGIONAL ANALYSIS

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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 regional energy and environment policy design and analysis--or, in a broader sense, the development of a coherent, realistic approach to energy/environment system management. The outputs of this research program include concepts, applied methodologies, and case studies.

During 1975-1976, 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 USA. The IIASA research was conducted within a network of collaborating institutions composed of the Institut für Energetic, Leipzig; the Institut Economique et Juridique de l'Energie, Grenoble; and the University of Wisconsin, Madison.

During 1976-1977, a fourth case study was emphasized, focusing on a different region, namely, Austria. The IIASA research for Austria was conducted with a network of collaborating Austrian institutions covering the fields of economics, demography, energy, and environment.

This report is concerned with the description of an air pollution dispersion methodology designed for regional analysis. It concentrates on a systems approach to short-range air pollution dispersion for long-term policy analysis of air pollution issues. The research evolved during the case study work at IIASA and was enriched by it.

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

The study was supported by the Austrian National Bank.

SUMMARY

The purpose of this work is to develop a methodology, the smeared concentration approximation (SCA) method, to allow the inclusion of air pollution dispersion in the long-term analysis of air pollution impacts without the direct use of complex and large air pollution models. The SCA method is intended for use in models and analysis concerned with long-term policy analysis and where simulation is one of the important techniques employed.

It is important for environmental impact analysis to include the transport and diffusion of the air pollutants. The SCA method centers around short-range transport or dispersion on the urban scale for each of three emission classes: low-level area sources, medium-level point sources, and high-level point sources. These three classes represent the most important divisions with respect to both air pollution dispersion and air pollution policy.

A central assumption of the SCA method is that a single spatially averaged exposure for an urban area is a sufficient indicator of air pollution exposure for long-term policy option analysis. SCA dispersion parameters are developed for calculating the spatially averaged exposure due to the emissions from each of the three emission classes. The development of the SCA dispersion parameters is discussed in detail and the most important feature of the SCA method is demonstrated, namely, that a minimum of detail is required, i.e. only the total urban emissions in each emission class is necessary.

The SCA dispersion parameters are presented in the form of an SCA dispersion kit to allow the parameters to take into account differences in meteorology (thus dispersion) for different regions. For the high-level point sources a stack height adjustment factor is included because stack heights of power plants are part of the environmental policy considerations.

Initial validation of the SCA method indicates that the spatially averaged exposure calculated by the means of the SCA dispersion parameters is within 20% of the spatially averaged monitoring data. Two examples of air pollution policy analysis based on case studies are presented showing the two major ways the SCA method should be used: regional policy analysis and single urban analysis. In addition, an example is worked through in Appendix A to show how the SCA dispersion kits are used to develop each SCA dispersion parameter for the three emission classes.

The Smeared Concentration Approximation Method: A Simplified Air Pollution Dispersion Methodology for Regional Analysis

R.L. Dennis

I. INTRODUCTION

Consideration of environmental impacts cannot be just for short-term management analysis after other fundamental planning decisions have been made. Decisions made from a short planning horizon can produce unwanted long-term impacts. Environmental scientists are pointing out that an incremental change in environmental stress may not produce just an incremental response of the ecosystem. Environmental considerations, therefore, must be systematically included in long-range planning, for example in energy system planning. Present data and model inadequacies, however, constrain the capability to provide useful assessment and policy information for long-range strategy analysis. Additionally, many of the available models are unsuited for such long-range analysis, being too complex to operate, too data intensive, or too site-specific. For energy system analysis specifically, models and methods need to be developed that are expressly designed for long-range policy analysis. These should be simple, flexible, and require a minimum of data; they would complement the existing models and methods.

One environmental impact, air pollution, is a major environmental concern for long-range energy planning. Adequate methods for air pollution analysis of strategic energy options are lacking. It is very important to model air pollution transport and dispersion. Since concern is about damage or environmental impact assessment, only analyzing emissions of air pollutants is inadequate. What matters is how the emissions are distributed and dispersed; what is desired is the exposure that produces the damage impact. This permits the assignment of responsibility for damages to different sources, it facilitates the assessment of strategies relative to air pollution impacts, or it indicates constraints on strategy options based on air pollution impacts. It has been difficult to include air pollution transport and dispersion in large analysis efforts concerned with long-range planning because the dispersion models, themselves, are usually large, site-specific, and data intensive. Thus it is usually considered too cumbersome and costly (time, money, and effort) to include air pollution dispersion on a routine basis in strategy analysis.

The purpose of this work is to develop a methodology, the smeared concentration approximation (SCA) method, to allow the inclusion of air pollution dispersion in the analysis of air pollution impacts without the direct use of complex and large air pollution dispersion models. What is needed is a simplified method to account for air pollution dispersion that is easily usable by a range of models and modelers that are engaged in multifactor or interdisciplinary planning analysis. The method should contain the essential and relevant features of air pollution dispersion, yet result in a simple, usable algorithm. The requirements for the method are thus:

- Simplicity,
- Inclusion of the essentials of dispersion, and
- Relevance for different meteorological conditions.

The SCA method has been developed to model the dispersion of air pollutants with these three requirements in mind. The work centers around air pollution dispersion at the urban scale; the impact on an urban area of air pollution arising from within it. The SCA method is tailored for modeling and analysis efforts concerned with evaluating long-range planning, where one important technique is the use of simulation. Examples of these types of models or analysis efforts are:

(1) Brookhaven Energy Systems Optimization Model (BESOM) [1];

(2) WISconsin Energy Model (WISE), a simulation model [2];

(3) An Economic-Environmental Planning Manual for Counties, States and Metropolitan Areas, a residuals management model [3]; and

(4) The IIASA Austrian Regional Energy/Environmental Study [4,5].

The description of the SCA method is the topic of this paper.

The SCA Dispersion Parameter

The SCA method is based on the proposition that a spatially averaged ground-level concentration (average exposure) is appropriate for long-term analysis, i.e., a smeared concentration approximation is adequate.

The SCA method determines two basic features:

- the extent of spatial averaging in defining an exposure, for example, should the spatial averaging be concentric rings and if so, how should they be defined.

- the degree of disaggregation of the exposure into different basic parts based on dispersion characteristics and policy considerations, for example, how many different categories of emissions heights should be used.

These two features set the framework of the SCA method which is discussed in section II.

Given the framework determined, SCA dispersion parameters are quantitatively defined for calculating the desired exposures. The SCA dispersion parameters have units of exposure per unit of emission ($\mu g/m^3$/ton). Validated air pollution dispersion models are used to develop the SCA dispersion parameters. This is done in three stages: first, using the dispersion models, spatially detailed ground-level concentrations are calculated. Second, these ground-level concentrations are spatially averaged to define a measure of exposure. Third, this SCA exposure is normalized by the total emissions input to the air pollution dispersion models, thus yielding the SCA dispersion parameter.

The SCA dispersion parameters are designed to replace the types of detailed air pollution dispersion models that are used for quantitatively developing the parameters. In addition to developing the SCA dispersion parameters, the detailed air pollution dispersion models are used for sensitivity studies of the SCA dispersion parameters. The sensitivity studies describe the response or lack of response of the SCA dispersion parameters to variations in important variables of the air dispersion system. The sensitivity studies assess the robustness and the uncertainties associated with the SCA dispersion parameters and help determine the range of applicability of these parameters. The focus of this paper is the quantitative development of a set of SCA dispersion parameters, together with a description of important sensitivity studies for these parameters.

The Geographic Scale

There are many scales for which SCA dispersion parameters could be developed, for instance:

- interregional (long-range pollutant transport on the continental scale);

- regional (long-range pollutant transport at the national or sub-national scale);

- urban (local pollutant transport);

- intra-urban (sub-local pollutant transport within an urban area).

The urban scale was chosen for the first development of the SCA dispersion parameter, for several reasons. Large urban areas tend to have the greatest air pollution problems. Knowledge of what is occurring at the urban scale can be important in standard setting and control strategy analysis. A method is needed for including transportation and space heating impacts in studies where the energy system as a whole is being analyzed. Solely considering air pollution impacts due to electricity production disregards important factors for policy analysis. There is a great deal of interest in human health impacts due to energy-related air pollution emissions. People who are concentrated in urban centers, thus creating the urban air pollution problem, have the greatest exposure per capita for most pollutants.

The Intent of the SCA Method

The SCA method is intended as a tool for policy analysis that is simpler and easier to use routinely than alternative methods for modeling air pollution dispersion. Since the urban scale was chosen, the SCA method is primarily intended for regional studies in which there are important urban population concentrations and for individual urban studies for which a long-term or a first-cut analysis of air pollution problems is desired. The method is intended to help achieve a balanced perspective in the analysis of impacts stemming from air pollution emissions of all types at the urban scale. The SCA method is designed for application to urban nonreacting or slowly reacting air pollutant species. Additional assumptions exogenous to the SCA method are needed when chemical reactions are involved.

The rest of the paper is organized as follows. Section II outlines the general framework of the SCA method. The approach and basic assumptions are given that underline the development of an SCA dispersion parameter and that help the SCA method meet its three requirements. Sections III, IV, and V describe in detail the SCA dispersion parameter development for area sources of air pollution emissions, medium-level point sources and high-level point sources, respectively. The results of detailed dispersion model calculations are presented with relevant sensitivity studies. An SCA dispersion parameter kit is set out at the end of each section. This kit comprises the basic building blocks of the SCA dispersion parameter. The final section discusses the validation of the SCA method and describes how it can be used. Finally, in Appendix A, a step-by-step description of the use of the SCA dispersion kits to construct the SCA dispersion parameters is provided for a sample set of meteorological statistics.

II. THE SCA METHOD: FRAMEWORK

As stated above, the requirements for the SCA method are that it is simple, contains the essential features of dispersion, and is relevant for different meteorological conditions. These three requirements will be discussed in connection with the associated assumptions fundamental to the SCA method. It is this set of assumptions that guides the operational formulation of the SCA dispersion parameters and that gives the SCA method its flexibility and generality.

Simplicity

The simplicity of the SCA method is associated with one central assumption, i.e., that it is sufficient to calculate a single spatially averaged ground-level air pollution concentration for an urban area. This spatially averaged ground-level exposure provides sufficient detail to compare air pollution impacts between cities in a region, to compare the evolution of air pollution impacts over time in a region and to compare air pollution impacts for different alternative futures generated for a study region.

This spatially averaged exposure is the collective exposure of the urban area, or the average exposure an average person or building receives. Essentially, we have assumed that the mobility of the population in an urban area is high relative to the spatial variation of the ground-level pollution concentrations. Thus a single spatially averaged measure is adequate for each urban area. Normalizing this single spatially averaged exposure ($\mu g/m^3$) by the total urban emissions (tons) causing that exposure is the basis for defining an SCA dispersion parameter (units of $\mu g/m^3/ton$). A visualization of the single exposure level associated with each urban area is shown in Figure 1.

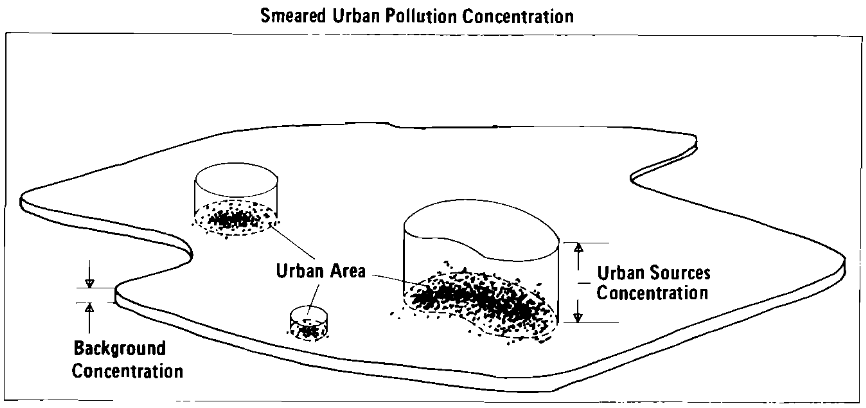

Figure 1. Single, spatially averaged urban exposure adding to a flat rural background concentration.

Admittedly, some people in an urban area will consistently experience conditions worse than average, while others will experience conditions consistently better. The errors incurred by making the averaging assumption depend upon the nature of the function relating damage to exposure--if the function is linear the error is less than if it is nonlinear, e.g. with a threshold. A greater refinement of the single urban exposure could be made to reduce this error (this can still be done exogenous to the work developed here); however, given the intent of the SCA method for long-range analysis and given the insight to impact analysis that the SCA method can provide using a single exposure per urban area, such a refinement is not considered to provide an improvement commensurate with the extra complexity and work required.

Essence of Dispersion

The essence of dispersion is retained in the method, while still permitting simplicity, by defining three classes of SCA dispersion parameters to match three classes of emission sources and by using the SCA dispersion parameter to calculate an annual average ground-level exposure from annual emissions for the urban area.

Three Classes of SCA Dispersion Parameters

For an urban area most sources of emissions automatically fall into three classes. They are:

1. Low-level area sources, as for example, transportation and residential emissions;

2. Medium-level point sources, as for example, industrial and district heating stacks; and

3. High-level point sources, as for example, large electricity generating plants.

The dispersion characteristics of these three are generally distinctly different; the differences within a particular class are smaller than the differences between classes.

It is the difference between the three classes that contains the essential features of dispersion (and requires going beyond quantities of emissions for impact analysis). As a rule of thumb (to be developed in more detail later), a ton of pollutant emitted in an urban area by a source in class 1 has ten times the effect on the urban area impacts as a ton emitted from class 2, and a 100 times the effect as a ton emitted from class 3. The three classes of sources are illustrated in Figure 2.

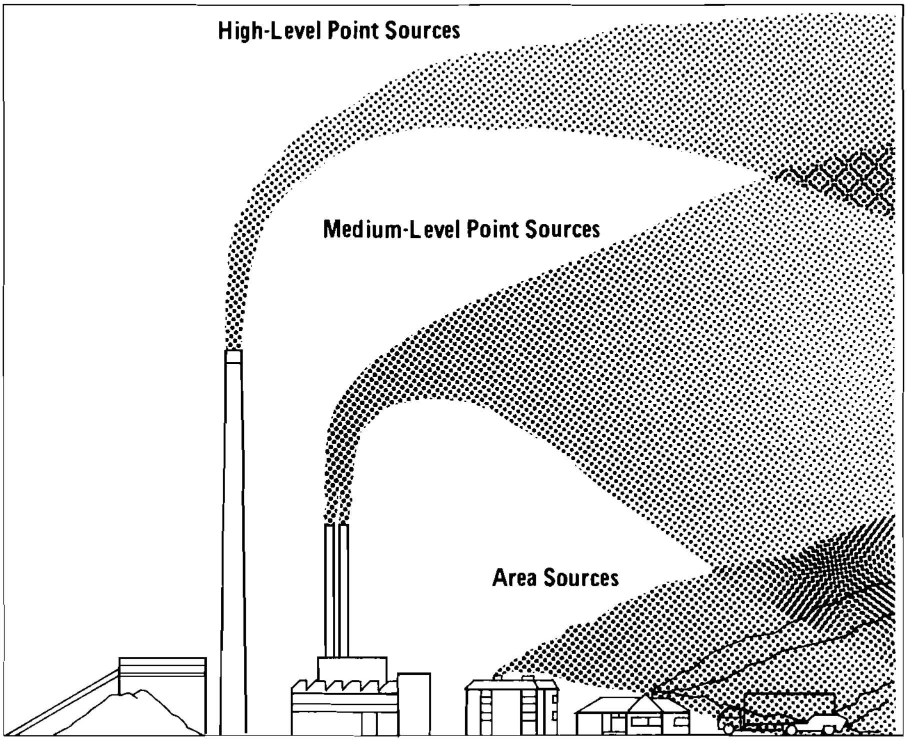

Figure 2. The three classes of emission sources.

More classes of emission sources (and correspondingly, SCA dispersion parameters) could be defined, but not enough additional information is gained at the policy and impact level. Too great an uncertainty also exists at the dispersion level. For example, cars may be twice as impact intensive as home space heating from a general dispersion point of view, because they are nearer the ground. There is great uncertainty, however, in the details of the concentrations produced on the streets, due to canyon effects and wind tunneling; plus, people live away from the street or above it. A quantum jump in data requirements would occur without a corresponding quantum jump in policy and impact understanding. For these reasons, it is better to keep the cars in the same class as homes, and to develop SCA dispersion parameters for just three classes of emissions sources: low-level area sources, medium-level point sources, and high-level point sources.

The three classes of SCA dispersion parameters permit analysis of the essential features of air pollution transport and dispersion. The fundamental differences in dispersion characteristics for air pollutants emitted from various sources contained in the differences in the SCA dispersion parameters associated with each of the three classes of emission sources. Importantly, policy considerations and control strategies fall quite naturally into these three classes. This differentiation is also sufficient to make policy relevant assignments of relative responsibility for air pollution impacts.

Use of Annual Average Concentrations

For most purposes it is sufficient for a long-term analysis to calculate an annual, spatially averaged exposure that results from each emission class. Although damage functions may require shorter temporal averages, Larson has observed that the distribution within a year of air pollution concentrations averaged over times shorter than a year can be approximated as log-normal distributions [6]. Any shorter-term average can thus be derived from the annual average by using the standard geometric deviation. This is shown in Figure 3 for 24 h averages. Any longer-term average (for damage from chronic exposure) can be derived from the accumulation of annual averages.

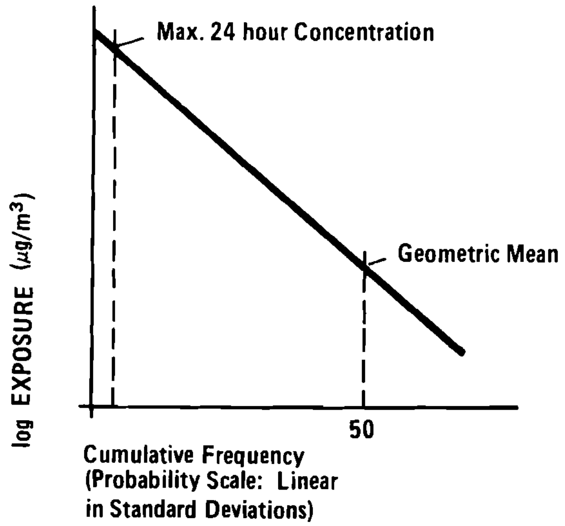

Figure 3. Log-normal relationship between annual and twenty-four-hour averages.

The use of the SCA dispersion parameters is not constrained, however, to calculating annual average exposures. As explained in the next section, the SCA dispersion parameters are formulated on the basis of wind speed and atmospheric stability. How the SCA dispersion parameter is composed for each emission class depends on the meteorological frequency factors used, e.g., the frequency of occurrence of different wind speeds and atmospheric stability can be for seasonal averages of meteorological conditions. The resulting SCA dispersion parameter would calculate a seasonal exposure (average $\mu g/m^3$/season) for seasonal emissions (average tons/season) and seasonal meteorology (average frequency factors/season). Individual worst case meteorology can also be analyzed. But, for this latter application the SCA dispersion parameters may well be too coarse to use, because of the spatial average, without some exogenous calibration. If there are strong objections to using seasonal or annual averages combined with the assumption of log-normality of the concentration distribution for shorter time averages, then one must carefully examine the problem being addressed. One should then ask if the SCA dispersion parameters are not being used beyond the valid range of analysis for which they are designed via the SCA method.

Responsiveness to Meteorology

The relevance for different regional and local meteorology is obtained by making a meteorology or dispersion "kit" for constructing the SCA dispersion parameter of each emission class. The purpose of the SCA dispersion kit is to allow the forming of a composite SCA dispersion parameter that takes into account the frequency of occurrence in time of the different meteorological conditions. Each building block in the SCA dispersion kit for emission class (i) consists of an SCA dispersion parameter, D_{ikm}, formulated for a particular atmospheric stability condition (k) and a particular wind speed (m).

A simplification of the meteorological statistics can be made without a loss in the general accuracy of the calculations [7]. The atmospheric stability is thus defined by three general subdivisions. They are:

k = 1: unstable atmosphere,

k = 2: neutral atmosphere,

k = 3: stable atmosphere.

The wind speed is defined by four general subdivisions. They are:

m = 1: high wind speed (> 7.5 m/s at 10 m height),

m = 2: moderate wind speed (5 - 7.5 m/s),

$m = 3$: low wind speed (2 - 5 m/s),

$m = 4$: very low wind speed and/or calm (below 2 m/s).

For a particular region, the SCA dispersion parameter for emission class (i) is composed by multiplying each D_{ikm} by the frequency of occurrence of the twelve (3×4) possible combinations of atmospheric stability (k) and wind speed (m) and then summing the results, as shown in Equation (1).

$$D_i = \sum_{k,m} ff_{km} D_{ikm} \tag{1}$$

where ff_{km}(= meteorological frequency factor) is the frequency of occurrence in time of the particular atmospheric stability, k, and the wind speed, m. Here D_i will be termed the composite SCA dispersion parameter. The precise exposure that D_i calculates, e.g., average winter exposure or average annual exposure, thus corresponds to the total time period used in collecting and averaging the meteorological frequency factors.

The D_{ikm} are formulated for a uniform wind-rose. This is the most general formulation, especially since a spatially averaged exposure is used. The important consideration for long-term analysis is the change of average exposure with time. The spatially averaged exposure of low-level area sources is actually already insensitive to the wind rose. The assumption of a uniform wind rose can add an element of uncertainty for the spatially averaged exposure from point sources [8]. In very extreme cases, this uncertainty could be up to a factor of two; however, this uncertainty is less than the uncertainty in most, if not all, damage functions. If deemed necessary, wind rose effects can be taken into account on an urban case-by-case basis by properly weighting the SCA dispersion parameters for each combination of atmospheric stability and wind speed.

The guiding principle in developing and applying the assumptions basic to the SCA method is that only the minimum detail should be retained. Refinements can always be made, but they should be proven necessary for dispersion or policy analysis reasons before being added to the existing framework. The framework presented in this section is considered to lay the basic structure for the formulation of the SCA dispersion parameters. The next three sections detail the development of the three classes of SCA dispersion parameters and demonstrate the great generality of the SCA dispersion parameters.

III. SCA DISPERSION PARAMETER DEVELOPMENT: AREA SOURCES

In this section the SCA dispersion parameter for area sources, D_1, will be described in detail. The first three parts of the section will demonstrate:

- D_1 is not sensitive to the location of the emissions in an urban area.
- D_1 is not sensitive to the surface roughness of the urban area.
- D_1 is dependent on the average radius of the urban area.

Finally, the SCA dispersion kit for constructing the composite D_1 will be presented.

The formulation of D_1 and the sensitivity studies for it were made with an air quality simulation model based on the gradient diffusion equation, which requires a numerical solution (sometimes called a K-model or a multiple-box model). The model was developed at the University of Wisconsin and has been accredited by the US Environmental Protection Agency (USEPA) [9]. A summary description of the diffusion equation and the method used to solve it are given in Appendix C1. The model was designed to treat dispersed emissions (area sources). It explicitly includes the treatment of the wind profile and the turbulent diffusivity profile as a function of height above the earth's surface, and it also treats the dynamic turbulence effects of surface roughness. A discussion of such models is included in [10] and [11].

Insensitivity to Urban Emission Location

Urban Emission Detail

It is clear that the location of the emissions in a city will be important in determining the concentration at any one point in the city. It is not immediately evident, however, if the emission location is important for determining the spatially averaged ground-level exposure for the city. A number of computer simulations were carried out for several different model cities and a model of a real city to determine the answer to this question. The result of these sensitivity studies was the very interesting and robust conclusion that the urban spatially averaged ground-level concentration was insensitive to any of the locational details of the urban emissions. For very large changes in the pattern of emissions, there was only a small change in the urban average, the range being never more than the order of ±10% for any given set of meteorological conditions.

Emission density patterns ($g/m^2/s$) for five different model cities, each with a radius of 10 km, were developed for these sensitivity studies (i.e., cities with 600,000 to 2,000,000 inhabitants). Additional transportation network emission density configurations and additional model cities were developed for several other radii to check the generality of the results. Cross-sections of the emission densities of the five model cities are shown in Figure 4.

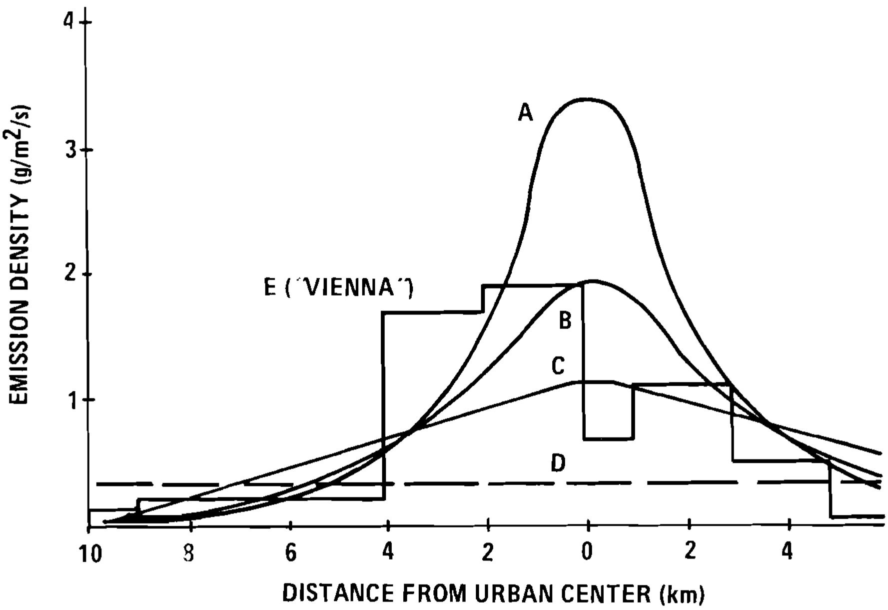

Figure 4. Emission density cross-sections for the five model cities.

All of the cities except model city E (a model of Vienna) are symmetric. From tests with the model city for Vienna it was clear that no loss in generality occurred due to the use of symmetric model cities. Model city A and B are based on the concept of a negative-exponential city [12] used by many urban geographers. Model city C is a linear city, i.e. the emission density decreases linearly from the center. Model city D is a uniform city; the emission density is constant over the entire city. Model city E is a model of Vienna--the pattern of emission density is shown in more detail in Figure 5. Only nine emission density divisions are shown in Figure 5, although in the model there are actually eighteen different divisions. For comparative purposes the emission densities of the five model cities are adjusted so that the total emissions are equal--the integral under each curve in Figure 4 is the same.

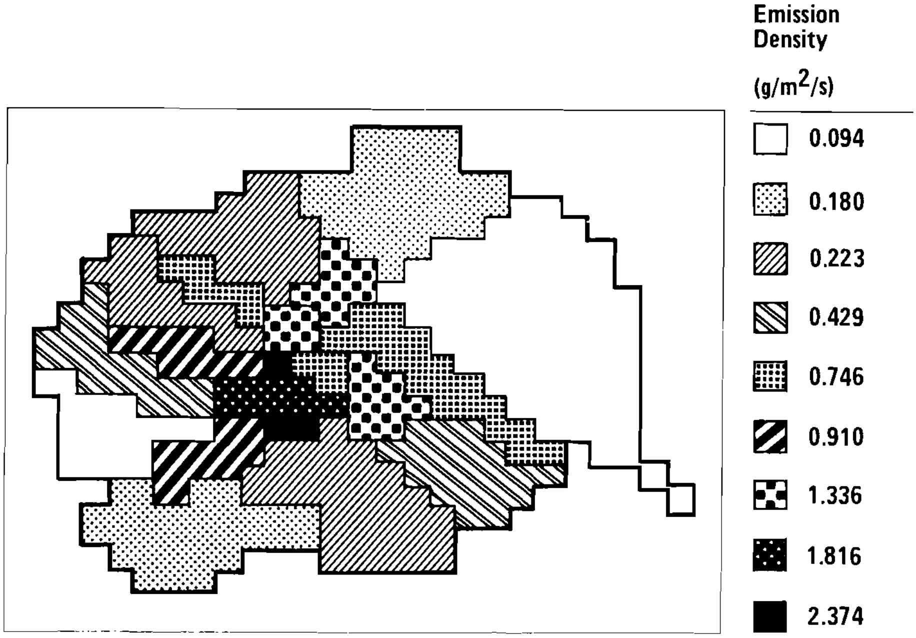

Figure 5. Emission density pattern for the model of Vienna, Austria.

Given the emission density distributions of the model cities as input, the box dispersion model simulated the ground-level air pollution concentration for each of the twelve combinations of atmospheric stability and wind speed. For each case, the ground-level concentration was spatially averaged over the urban area and normalized by the total emissions, giving D_{1km}--exposure per unit of emission rate ($\mu g/m^3/t$ per unit time).

If one compares the ratio of the maximum concentration to the spatially averaged concentration for the different model cities, as expected there is a great variation in the results (see Table 1). For example, model cities A and C have nearly identical ratios of maximum to minimum emission density, but the maximum emission density of city C (Figure 4) is three times lower than city A's. Yet the ratio of the maximum concentration to the spatially averaged concentration for city C is 2.1 times lower than city A's ratio. Vienna's emission density ratio is less than half city A's ratio, yet the ratios of the maximum to the spatially averaged concentrations are nearly the same for both cities. It is also noteworthy that the concentration ratios do not change for different wind speeds.

Table 1. Comparison of variability of inputs and outputs for the five model cities.

Model Cities	Input (Emission Density) Maximum to Minimum Ratio	Output (Concentration) Peak to Urban Spatial-Average Ratio Stability: Neutral Wind Speed	
		Low	Moderate
A	82.0	6.3	6.4
B	29.8	4.5	4.6
C	82.3	3.0	3.0
D	1.0	1.4	1.4
E	38.5	6.0	6.1

On the other hand, Figure 6 shows the results for D_{1km}, exposure per unit of emission per unit time; the variation is much less than would have been expected. The D_1's are shown for three sets of meteorological conditions. The range of variation about the mean for each meteorological set is ±10%. Although Vienna's emission density ratio was larger than city B's and although Vienna's concentration ratio was the same as city A's, the D_{1km}'s in each category for Vienna are very close to that of the uniform city (city D). The implication is that most real cities have a patchiness of emission densities for area sources that counteracts the large concentration ratios and thus their normalized spatial averages for low-level sources (D_1's) will tend to be in the range between city C and city D.

The conclusion can be drawn that the normalized spatially averaged urban ground-level concentrations (the D_1's) are insensitive to the details of the emission density location within the urban area. This means that the D_1's can be used without analysis of the location of the emission densities, thus emissions, in an urban area. It is sufficient to know just the total quantity of emissions that are emitted in the time period being considered for the given city.

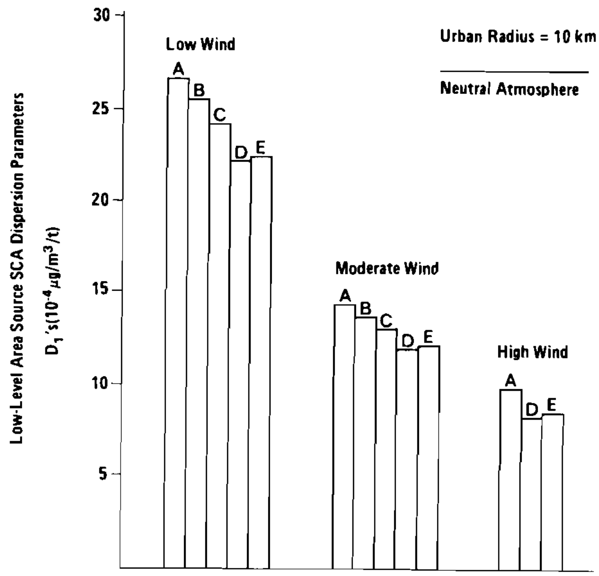

Figure 6. D_{1km}'s for the five model cities for selected meteorological conditions.

Treatment of Urban Surface Roughness

Surface roughness is defined as [12]:

$$z_0 = \frac{Ha}{2A} , \tag{2}$$

where H is the effective height of roughness elements,

a, the frontal or silhouette area seen by the wind, and

A, the lot area (i.e. the total area of region divided by number of surface roughness elements).

A doubling in the effective height of buildings (more than doubling the physical height) or a doubling in the number of buildings, keeping the average height constant (i.e. doubling the density), will quadruple the surface roughness of an urban area.

The surface roughness of a city will affect dispersion of pollutants and thus the predicted pollutant concentration at particular points within the city. It would, therefore, be of interest to know if the spatially averaged ground-level concentration for an urban area is sensitive to differences in surface roughness. The computer simulation of the effect that doubling and then quadrupling the surface roughness would have on the normalized spatially averaged ground-level concentrations (D_1's) is shown for model cities A, B, and D in Figure 7.

Category 1 in Figure 7 corresponds to cities with predominately one- to three-story buildings; category 3 corresponds to cities with predominately four- to eight-story buildings. Within each combination of atmospheric stability and wind speed and any one city type, the variation about category two is less than ±7%. If one is interested in the variation of D_1 with time as a city changes or grows, one should compare categories 1, 2 and 3 for a given city type. Such a comparison suggests that the variation in D_1 will be negligible.

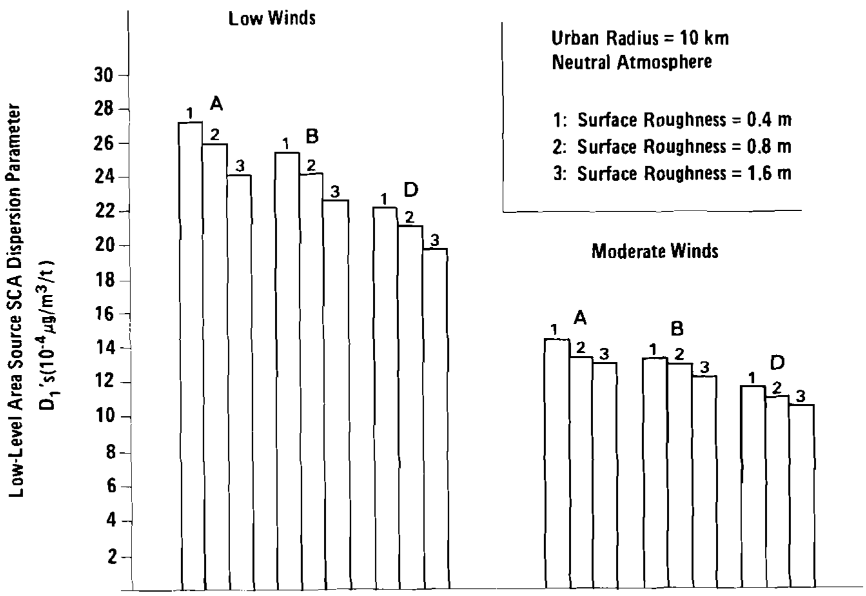

Figure 7. D_{1km}'s for three model cities as a function of average-surface roughness.

The main influence of surface roughness on the low-level SCA dispersion parameter would result from differences in roughness between cities of the same area, but greatly differing building densities. In such a case, a comparison, within each set of meteorological parameters, is better made between low-level SCA dispersion parameters for different city types, rather than between low-level SCA dispersion parameters of the same city type. The city with the lower density, thus with lower surface roughness, would most likely be more uniform with respect to building types than the more dense city. As surface roughness decreases, the ratio between the maximum and minimum emission densities would also decrease. The suggested comparison would be between city type A, category 3 and city type B, category 2. For all meteorological conditions, the difference can be less than the difference within a single city type, e.g., there is almost no difference between A-3 and B-2. One may conclude that it is not necessary to consider differences in surface roughness between cities when one employs D_1--a single value for a given urban area is adequate.

The fact that one really does not need to account for details of the urban area, such as emission location and surface roughness, in order to estimate an average exposure to air pollutants gives the SCA method a large measure of applicability and robustness. This reduces data requirements to a minimum without sacrificing any essential features of dispersion phenomena.

Form of the Low-Level Area Source SCA Dispersion Parameter

It has been shown above that the low-level area source SCA dispersion parameter, D_1, can be used without analysis of urban details such as location of emissions and surface roughness. An element of the air dispersion system that does affect the SCA dispersion parameter, D_1, is the size (or area) of the city. Independent of the quantity of emissions, the size of the urban area will affect the ability of the air mass above the city to dilute the emissions, thus influencing the spatially averaged ground-level concentration per unit of emissions. The average radius of an urban area is used as a parameter to represent its area. Figure 8 shows D_1 as a function of the average radius for model city A, the exponential city, and model city D, the uniform city. The same annual meteorological statistics were assumed for both city types in the computation of the composite D_1's.

It is clear from Figure 8 that D_1 is a strong function of the urban radius. The two curves shown, as would now be expected, lie close together. There is essentially no difference in the form of the curves, which is suggestive of a power law. The data

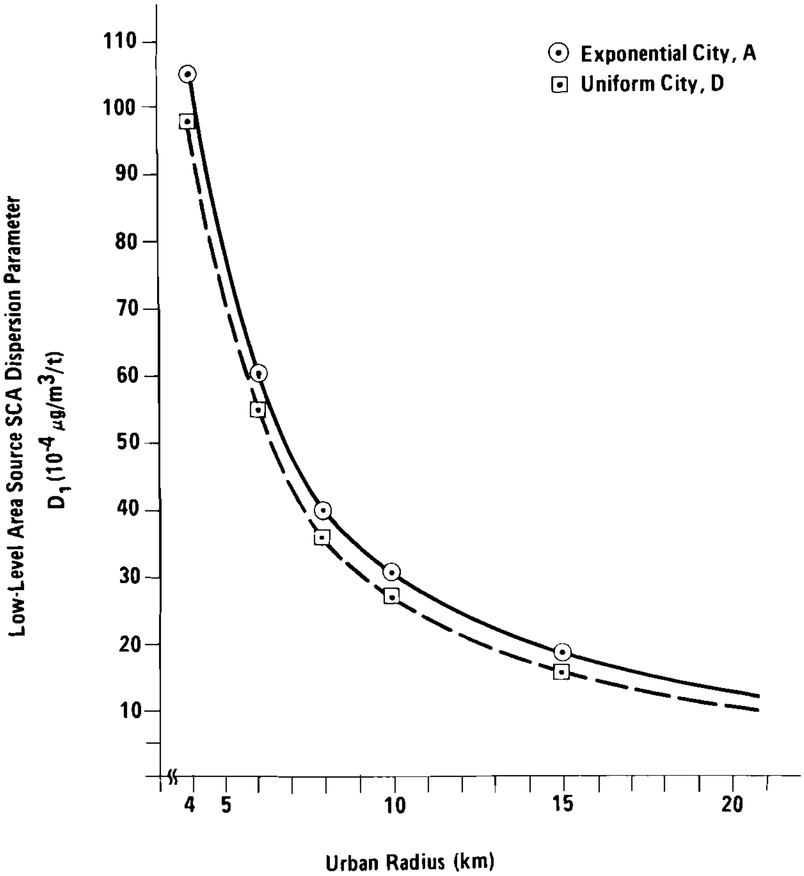

Figure 8. The composite D_1 as a function of average city radius for exponential city A and uniform city D.

used in Figure 8 is shown again in Figure 9 using a log-log scale, confirming that the relation between D_1 and urban radius is a power law with a negative exponent. In this example in Figures 8 and 9,

$$D_1(R) = 690\ R^{-1.39} \tag{3}$$

where D_1 has units of $10^{-4}\mu g/m^3/t$ per annum,

and R is the average urban radius in kilometers.

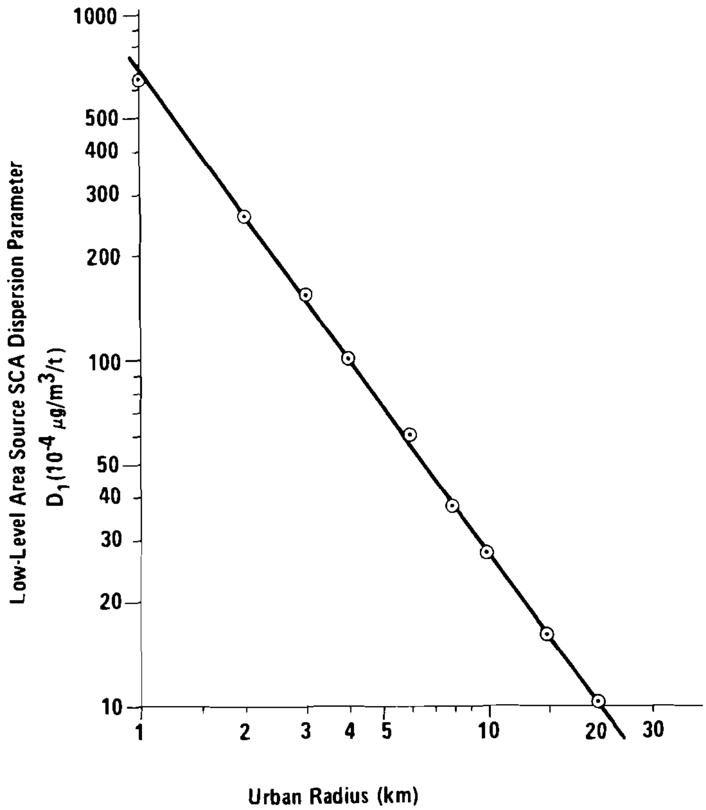

Figure 9. The SCA dispersion parameter D_1 as a function of average city radius.

As stated in section II, the dispersion parameter, D_1, is a weighted composite of the D_{1km}, one component for each of the twelve combinations of meteorological parameters (atmospheric stability, K, and wind speed, m). Figure 10 demonstrates that each of the individual low-level area source SCA dispersion parameters, D_{1km}, is a power law function of the average urban radius, R. Only one wind speed, with three atmospheric stability categories, is shown here, but the form is the same for all other combinations of atmospheric stability and wind speed.

Each line in Figure 10 is the graphical representation of an individual D_{1km} in the SCA dispersion kit for making up the low-level area source SCA dispersion parameter. The low-level area source SCA dispersion kit will be defined in the next section.

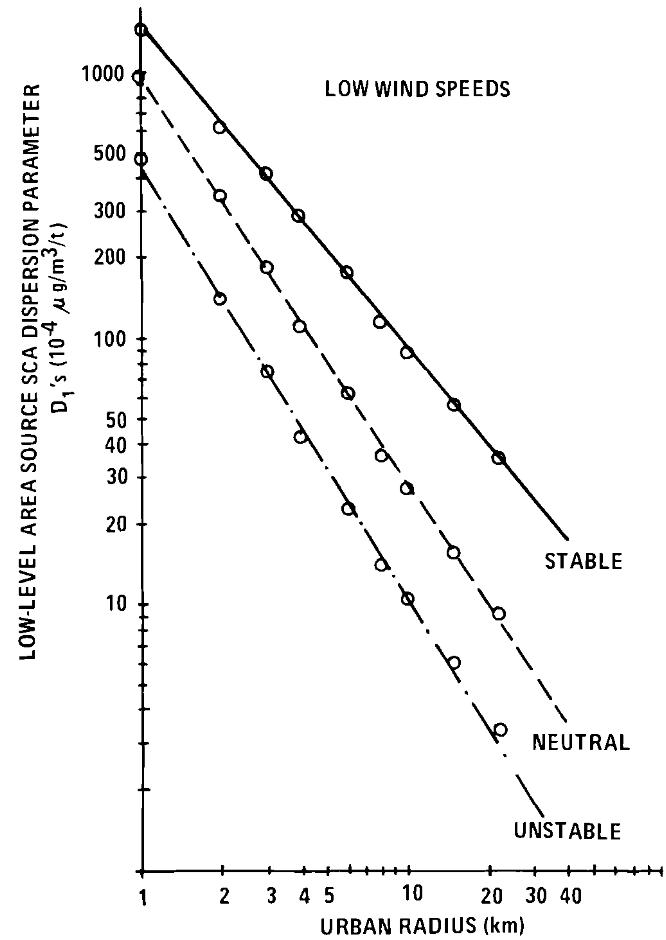

Figure 10. Area source SCA dispersion parameters for low wind speed and the three atmospheric stabilities.

Low-Level Area Source SCA Dispersion Kit

Each of the low-level area source SCA dispersion parameters, D_{1km}, for a given set of meteorological conditions, is a power law function of the urban radius. For later comparability, a different form of the power law is used to define the D_{1km}'s.

$$\ell n(D_{1km}) = a_{1km} + b_{1km}(\ell nR) \tag{4}$$

where k is the atmospheric stability,

m, the wind speed, and

R, the average urban radius.

The SCA dispersion kit coefficients, a_{1km} and b_{1km}, defined for each combination of atmospheric stability and wind speed constitute the SCA dispersion kit. These coefficients are given in Table 2. The units of the D_{1km} are in $10^{-4}\mu g/m^3/t$ per unit time--the latter determined by the time average subsumed in the meteorological statistics used to compose D_1 from the kit.

Table 2. Coefficients of the SCA dispersion kit for D_1, the low-level area source SCA dispersion parameter.

$$\ell n(D_{1km}) = a_{1km} + b_{1km}(\ell nR)$$

D: units of $10^{-4}\mu g/m^3/t$ per unit time

R: units of kilometers

Atmospheric Stability (k)	Wind Speed (m)	SCA Dispersion Kit Coefficients	
		a_{1km}	b_{1km}
Unstable	Very low Low Moderate High	6.3909 6.0746 5.9253 5.7998	-1.4922 -1.7241 -1.7124 -1.6815
Neutral	Very low Low Moderate High	7.7780 6.8432 6.2450 5.8925	-1.5919 -1.5998 -1.6191 -1.6236
Stable	Very low Low Moderate	7.3975 7.2562 6.9757	-0.8715 -1.2407 -1.4334

The values of b_{1km} imply that D_1 is a strong function of urban radius. The b_1's group together for each atmospheric stability class; differences due to wind speed within an atmospheric stability class are less than differences across atmospheric stability classes. The moderate wind, stable atmospheric case is of only theoretical relevance because this combination does not occur in stable conditions.

An example of the use of this low-level area source SCA dispersion kit with Equation (1) is given in Appendix 1. In this appendix examples of annual meteorological statistics (annual frequency of occurrence of atmospheric stability and wind speed) are given and the procedure for computing D_1 from the SCA dispersion kit is described and carried out. The low-level area source SCA dispersion parameter, D_1, derived by using the outlined procedure, is then given as a function of urban radius for the example set of meteorological statistics. Finally, the composite D_1's for urban radii of 10 km and 6 km are given for illustrative purposes.

IV. SCA DISPERSION PARAMETER D_2: MEDIUM-LEVEL POINT SOURCES

In this section the SCA dispersion parameter for medium-level point sources, D_2, will be described in detail. In the first five subsections, the following main features of the second SCA dispersion parameter are presented:

- D_2 is insensitive to the location of the point sources.
- D_2 is relatively insensitive to the mix of the point sources.
- D_2 is not sensitive to surface roughness of the urban area.
- D_2 is moderately sensitive to average stack height, but relatively insensitive to all other stack parameters.
- D_2 is dependent on the average radius of the urban area.

In the final subsection, the SCA dispersion kit for D_2 will be presented.

The calculations in this section were carried out with the aid of an air quality simulation model based on the so-called Gaussian plume equation (sometimes termed Pasquill-type model). Perfect reflection at both upper and lower boundaries is assumed and deposition is not included. Although this model has some weaknesses, it is easy to use, because it has an analytical solution, and represents ground-level concentrations well. The model used was programmed at the University of Wisconsin [13] and has been accredited by the USEPA. The model was designed to treat multiple point sources on a regional level. For medium-level point sources, the Moses and Carson plume-rise formula is used [14]. The basic air diffusion equations and the Moses and Carson plume-rise formula are given in Appendix C2.

For the calculations concerning D_2, model cities with a reference set of twenty-four point sources were used. The stack characteristics (height, top diameter, volume flow rate and exit temperature) of the twenty-four point sources were selected to represent a typical or average mix that would be found in larger towns and cities. This includes not only industrial stacks of various sorts, but also incineration stacks, venting stacks and district heating stacks. The stack characteristics of the reference set of point sources are given in detail in Appendix B1.

Insensitivity to Point Source Location

As with area sources of emissions, it is of interest to know if the SCA dispersion parameter for medium-level point sources is insensitive to the location of the point sources within the urban area. To check sensitivity to location a number of model city configurations using the reference set of point sources were developed. The locations of the point sources were combined in several ways, including concentration at the center of the urban area, concentration at the edge of the urban area and uniform location of the point sources throughout the urban area.

The results of these tests showed that D_2 is insensitive to the location of the point sources. The differences in D_2 for different location configurations and urban radii greater than or equal to 2 km were never more than ±5%. For larger urban areas, i.e. $R = 6$ km and greater, the differences in D_2 were less than ±2%--the differences decrease as the urban size increases. Larger differences in D_2 occur for urban areas that are small, i.e. radii less than 2 km. When the average urban radius is less than 1 km, D_2 does start to be seriously affected by differences in point source location. However, if one is working at a regional or national level, it is not sensible to deal with such small localities on an individual basis. Still, it is of interest to know the spatially averaged ground-level concentrations for medium-level point sources occurring in these small localities, and D_2 does represent this average situation. Therefore, for the average situation, D_2 can be considered to be insensitive to the location of the point sources for all urban radii.

Relative Insensitivity to Point Source Mix

Unlike area sources, medium-level point sources have a great variety of characteristics that affect their dispersal of air pollutants--stack height being only one. Different urban areas will have different mixes of point sources depending on types of economic activity. It is therefore important to check the sensitivity of D_2 to changes in the relative mix of point sources. The results of this check showed that D_2 is relatively insensitive to the point source mix. This means that the variation in D_2 was not large enough to warrant a more detailed basis for developing D_2; the reference set of point sources used to formulate D_2 adequately represents the various mixes of point sources.

To check the sensitivity of D_2 to changes in the relative mix of point sources, four model cities were defined in addition to the model city with the reference set of point sources. All or part of the reference set of point sources were used in defining the other four cities, but the emissions of the various point sources were weighted differently. Thus the five resulting model cities differ in number of point sources and in the relative magnitude of the emissions from the point sources. A representation of the five model cities denoting the maximum and minimum emitters is shown in Figure 11.

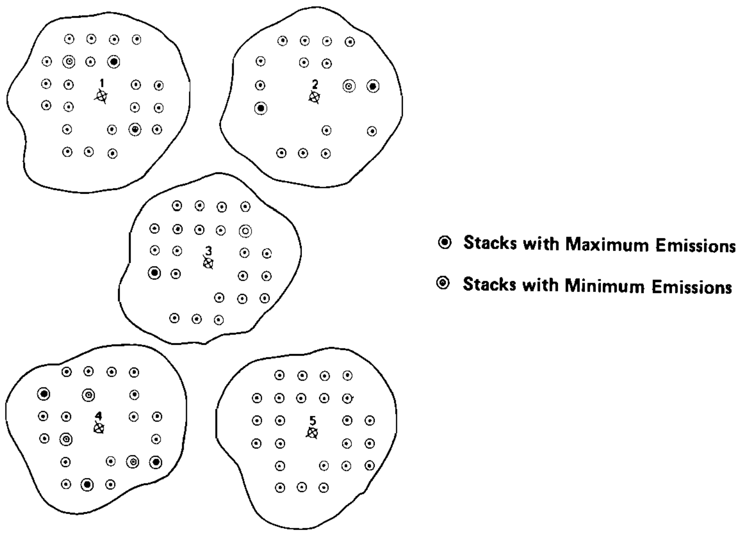

Figure 11. The five model cities representing different mixes of point sources.

Model city 5 contains the reference set of point sources. For this check the annual emissions per stack in city 5 are set equal to each other. The mix of stack and emission properties for the five model cities is more clearly shown in Table 3. The range of stack heights of the maximum emitters is quite large and the range between the maximum and minimum emissions is also large, large enough to differentiate the five configurations. The weighted average stack height is weighted by emissions--the weighted average stack height for city 5 is the arithmetic average of the twenty-four stacks.

Results of a sensitivity analysis for a neutral atmosphere and three winds speeds are presented in Figure 12. For low winds, the range of variation about the average was ±50%, for moderate winds ±30%, and for high winds ±25%. The range variation decreases as wind speed increases because atmospheric mixing is improved, overriding differences in dominant stack characteristics; this is also observed for the range of variation between stable, neutral and unstable atmospheric conditions. For a typical set of meteorological conditions, the variation in D_2 was of the order of ±28%. Additional sensitivity studies in which the mix of stack heights were varied, but not the other stack parameters, confirmed that this variation in D_2 was caused primarily by differences in the types of stacks that were the dominant emitters; i.e. the variation of ±28% did not significantly

Table 3. Main properties of the five model city point sources.

	Medium-Level Point Source Model City				
	1	2	3	4	5
Number of Stacks	23	16	23	21	23
Mean Emissions per Stack (t/year)	9.3	151	51	75	4
Maximum Emissions (t/year)	77	856	237	435	4
Minimum Emissions (t/year)	1	2	12	1	4
Weighted Average Stack Height (m)	48.5	37.4	37.6	27.3	32.9
Maximum Stack Height (m)	79	79	79	58	79
Minimum Stack Height (m)	8	12	8	8	8
Stack Height of Maximum Emitters (m)	79	30	44	15	79
Stack Height of Minimum Emitters (m)	8	53	24	16.7	8

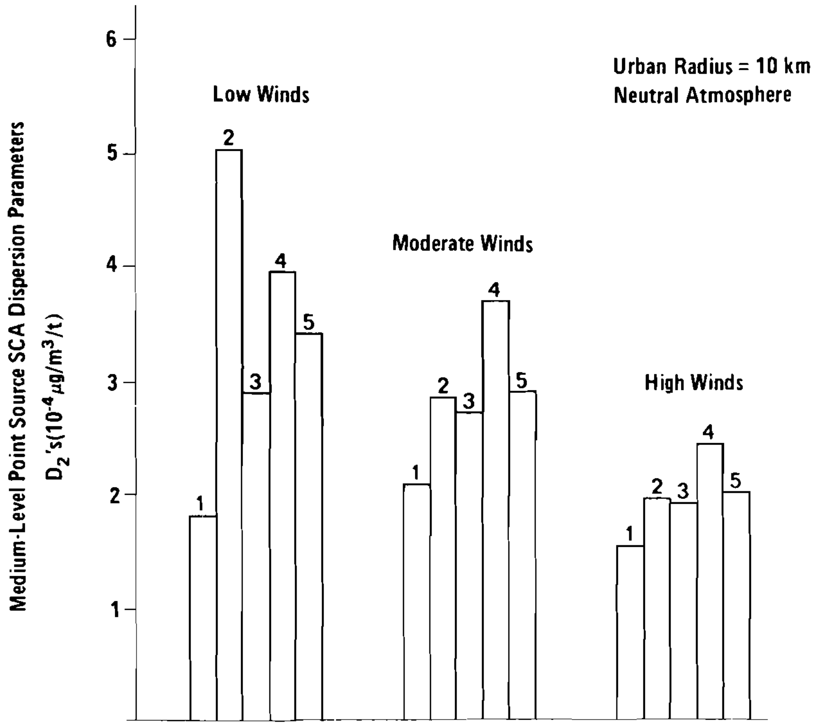

Figure 12. Medium-level point source SCA dispersion parameters for the five model cities and for given meteorological conditions.

change. The overall findings suggest, therefore, that the sensitivity of D_2 to the mix of the types of stacks is of the order of ±25 to ±30%.

Interestingly, the SCA dispersion parameter calculated for model city 5 (reference set of point sources each with equal emissions) was always within ±3% of the average of the other four configurations. With this in mind, the variation of ±25-30% was not considered large enough to warrant making a more detailed formulation for D_2. This variation is also much smaller than differences between the three dispersion classes. Thus, the reference set of point sources appears to adequately represent the dispersion associated with a mixed set of point sources.

The main two conclusions from this analysis are that D_2 is insensitive to point source location and relatively insensitive to point source mix. These are two important features of the SCA method. These conclusions reduce the data requirements for use of the SCA dispersion parameters to a minimum and, as for the area sources, give the SCA method the generality and simplicity desired. It should be noted once again that for the sensitivity studies presented here a uniform wind rose is assumed.

Insensitivity to Surface Roughness

To provide a parallel with the area source SCA dispersion parameter sensitivity studies, it is of interest to know if the medium-level point source SCA dispersion parameter is sensitive to surface roughness. Previous work [15] has shown that for point sources changes in surface roughness do not immediately affect the atmospheric dispersion occurring at the height of the point source plume. To have an effect, the change must occur more than ten effective stack heights (physical stack height plus plume rise) upwind for wind speed and 100 effective stack heights for diffusivity. Thus surface roughness effects should only be examined for urban areas with a radius greater than 4 km, i.e. at least half the distance across the urban area must be greater than 100 physical stack heights.

In the Gaussian model, the coefficients of dispersion that are normally used represent rural surface roughness because these coefficients are better known. To check the response of D_2 to surface roughness in urban areas, an extreme case was chosen: it was assumed that the surface roughness of the entire urban area and its surroundings was similar to a high-rise central city [16]. A comparison of D_2's calculated for rural surface roughness and for this "urban" surface roughness is shown in Figure 13. Here a neutral atmosphere and the four wind speeds at two different urban radii are shown. For this set of meteorological conditions the individual urban D_{2km}'s are up to 30% lower than the rural D_{2km}'s for an urban radius of 10 km and up to 23% lower for an urban radius of 30 km. The average difference between the urban D_2 and the rural D_2 as given in Figure 13 is 17% for R = 10 km and 22% for R = 30 km.

The difference between the rural and the urban D_{2km}'s is not the same for all meteorological conditions. This difference is less for unstable and stable atmospheric conditions. In Figure 14, the composite annual D_2 (the weighted average of D_{2km} over annual frequencies of occurrence of the 12 combinations of wind speed and atmospheric stability) is shown as a function of urban radius for the urban and rural surface roughness cases for a typical set of annual meteorological conditions. When the urban radius is 10 km the urban D_2 is only 5% lower than the rural D_2. At an urban radius of 30 km this difference becomes 15%.

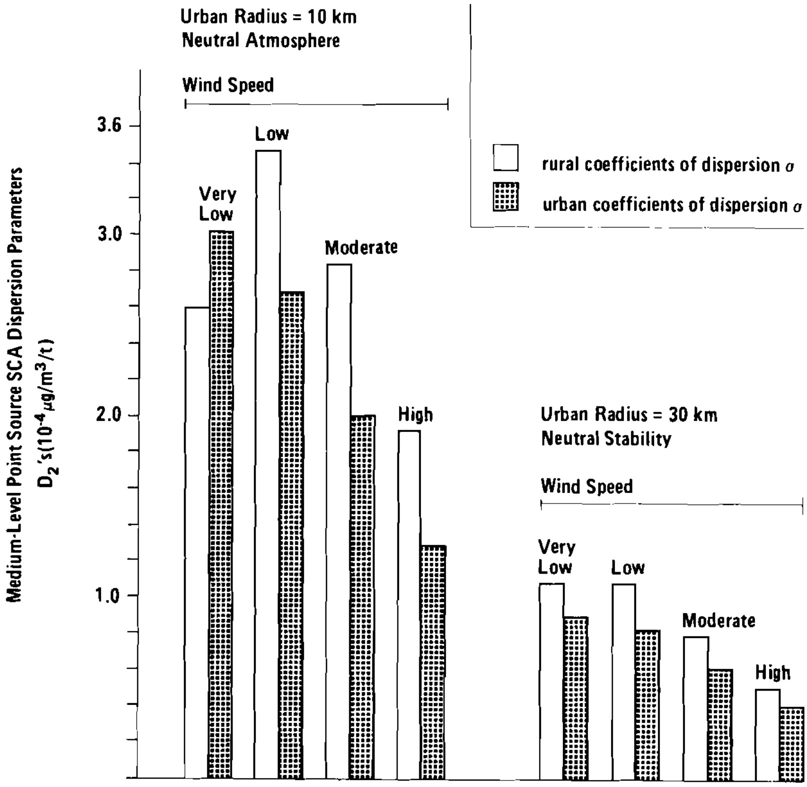

Figure 13. Medium-level point source surface roughness sensitivity for D_2 at two urban radii and a selected set of meteorological conditions.

The differences between an urban D_2 and a rural D_2 as shown in Figures 13 and 14 are larger than what would actually occur, because the surrounding area of a city and much of the city itself will not have the roughness of a high-rise central city. Thus fewer than half the point sources would be affected by any signficiant changes in the urban surface roughness. This means that for seasonal and annual types of meteorological statistics the difference between the D_2's for urban and rural surface roughness is expected to be less than 5%. For the SCA method, this is considered to be a neglible difference.

The sensitivity studies outlined in this section suggest therefore that the medium-level point source SCA dispersion parameter can be considered to be insensitive to the urban surface roughness. As the rural coefficients for the Gaussian model have a better empirical foundation and are widely accepted, the rural coefficients were used in the Gaussian plume model calculations for the development of the SCA dispersion kit for D_2.

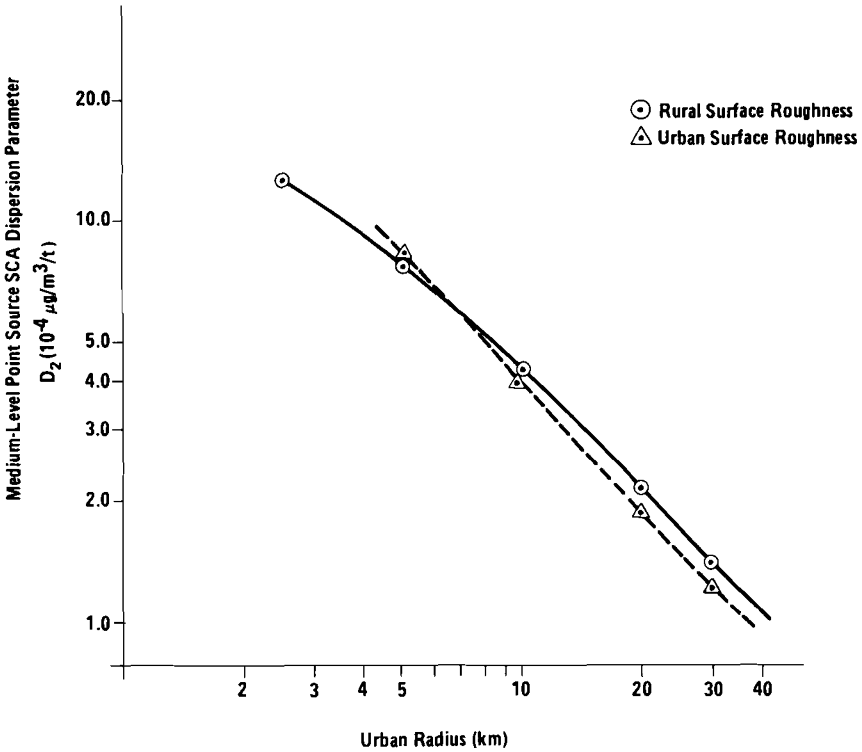

Figure 14. Composite D_2 as a function of urban radius for rural and urban surface roughness conditions.

Sensitivities to Stack Parameters

The SCA dispersion parameter D_2 is relatively dependent on the stack characteristics. It is moderately sensitive to average stack height, but is relatively insensitive to the other stack characteristics. These features of D_2 are shown in more detail in Table 4. The results are of course dependent on the Moses and Carson plume-rise formula used, so they are indicative of what might occur. The variations given in Table 4 are not considered to introduce an intolerable level of uncertainty to the dispersion parameter; only stack height has an average variation that is greater than ±30%. It is better to empirically calibrate D_2, if deemed necessary, than to alter D_2 on the basis of stack characteristics.

Stack height, however, is an important variable for policy considerations. Because environmental policies could force an increase in overall stack height of industrial point sources, it is of interest to know the response of D_2 to stack height for policy reasons. If F is defined as the ratio between the adjusted stack height average and the reference set stack height average, then adjustment factor for D_2 can be defined in terms of F. For $0.5 \leq F \leq 2.0$,

$$\text{Adjustment Factor} = 1.00 - 0.579 \ln F \quad . \tag{5}$$

The coefficient in front of $\ln F$ is not constant, but rather is a weak function of city radius; however, since the correction for radius is less than 10%, it can be neglected here.

Table 4. Sensitivity of medium-level point source SCA dispersion parameter to stack characteristics: percent change in D_2 relative to reference set D_2.

Stack Height	Stack Diameter
Reference Set Average = 32.9 m New Average: 16.4 m 49.3 m % Change in D_2: +40% -24% Average Effect: ±32%	Reference Set Average = 1.56 m New Average: 0.78 2.34 % Change in D_2: +19% -3% Average Effect: ±11%
Volume Flow Rate	**Exit Temperature**
Reference Set Average = 35.9 m^3/s New Average: 17.9 53.8 % Change in D_2: +23% -10% Average Effect: ±16%	Reference Set Average = 473 K New Average: 403* 573 % Change in D_2: +33% -16% Average Effect: ±24%

*The exit temperature was not allowed to go below 373 K due to corrosion arguments, unless the temperature was already below this value.

Form of the SCA Dispersion Parameter D_2

The form of the individual D_2's differs from a given combination of wind speed and atmosphere stability. For high wind speeds, the form of the D_{2km}'s as shown in Figure 15, is similar to the D_{1km}'s although the values are quite different (compare with Figure 10). For low wind speeds, however, the D_{2km}'s no

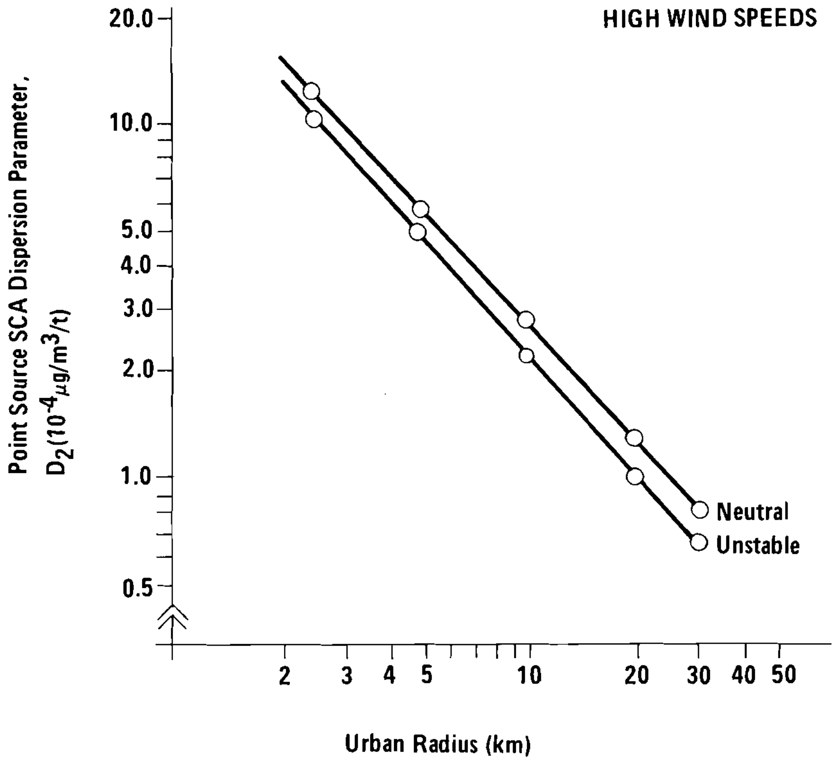

Figure 15. SCA D_{2km}'s for high wind speeds, illustrating similarities to D_{1km}'s.

longer plot as straight lines on a log-log scale as a function of urban radius. As illustrated in Figure 16, the lines representing D_{2km} begin to curve downwards as the radius decreases. As the urban radius decreases, the plume footprint is beginning to touch down more and more outside of the city for certain meteorological conditions. The composite annual D_2 for a typical set of annual meteorological conditions, Figure 14, does not show as strong a curvature as shown in Figure 16.

Medium-Level Point Source SCA Dispersion Kit

The equation that describes the D_{2km}'s must have more terms than the equation that describes the D_{1km}'s, since the D_{2km}'s no longer plot as straight lines on a log-log graph. Because the

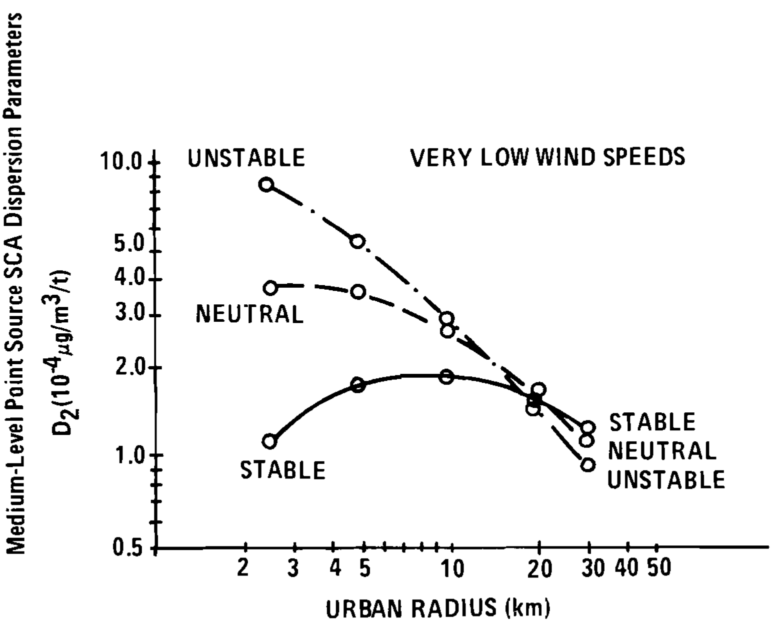

Figure 16. SCA D_{2km}'s for very low wind speeds, illustrating differences from the D_{1km}'s.

curvature in the D_{2km}'s monotonically increases as the urban radius decreases, it is sufficient to add only one more term to the equation that describes the D_{2km}'s. Now,

$$\ln(D_{2km}) = a_{2km} + b_{2km}(\ln R) + c_{2km}(\ln R)^2 \quad , \qquad (6)$$

where k is the atmospheric stability,

m, the wind speed, and

R, the average urban radius.

For D_2, the SCA dispersion kit coefficients, a_{2km}, b_{2km}, and c_{2km}, form the SCA dispersion kit, which is given in Table 5. Again, the units of the D_{2km}'s are $\mu g/m^3/t$ per unit time, the latter being set by the meteorological frequency factors when the kit is used to compose D_2. The wind speed classes for stable atmospheric conditions stop with low winds because higher wind speeds do not occur with moderate to strong stable atmospheric conditions.

Table 5. Medium-level point source SCA dispersion kit: D_2.

$$\ell n(D_{2km}) = a_{2km} + b_{2km}(\ell nR) + c_{2km}(\ell nR)^2$$

D: units of 10^{-4} $\mu g/m^3/t$ per unit time

R: units of kilometers

Atmospheric Stability (k)	Wind Speed (m)	SCA Dispersion Kit Coefficients		
		a_{2km}	b_{2km}	c_{2km}
Unstable	Very low	2.6037	-0.4189	-0.1112
	Low	3.2192	-0.8274	-0.0533
	Moderate	3.3518	-1.0820	-0.0074
	High	3.1275	-1.1379	0.0
Neutral	Very low	1.0435	0.4930	-0.2277
	Low	2.6678	-0.3045	-0.1340
	Moderate	2.9945	-0.6299	-0.0940
	High	2.8857	-0.8039	-0.0695
Stable	Very low	-0.7426	1.2169	-0.2785
	Low	0.8637	0.6345	-0.2300

Since one important element of the SCA method is the differentiation of emission sources into three emission classes, the contrast of a composite D_2 with a composite D_1 (and D_3) is discussed in Section VI. An example of the use of the SCA dispersion kit for D_2 is given in Appendix A2 for the same set of meteorological statistics as for Appendix A1. As in Appendix A1, a composite D_2 is derived and given as a function of urban radius and the specific values of D_2 for the urban radii of 10 km and 6 km are given.

V. SCA DISPERSION PARAMETER D_3: HIGH-LEVEL POINT SOURCES

In this section the SCA dispersion parameter for high-level point sources, D_3, will be discussed in detail. The first two subsections present the four main features of the third SCA dispersion parameter. These are:

- D_3 is moderately sensitive to location of the point sources.
- D_3 is insensitive to surface roughness.
- D_3 is sensitive to the stack height, but relatively insensitive to all other stack characteristics.
- D_3 is a weak function of urban radius.

In the final subsection, the SCA dispersion parameter kit for D_3 will be given.

The calculations in this section were made with the same model used for the D_2 calculations with one important difference. For D_3 the Briggs plume-rise formula [14] was used (see Appendix C2) becuase it better represents the plume behavior for tall stacks. One reference set of stack characteristics was used. The details are given in Appendix B2.

Urban Location and Surface Roughness

As one might expect, D_3 is more sensitive to the location of the point source or sources than D_2. If one compares D_3 for a point source at mid-center of an urban area with the D_3 computed for a point source at the edge of an urban area, the difference in the two SCA dispersion parameters is greatest at small urban radii and least at large urban radii: 41% at a radius of 2.5 km and 7% at a radius of 30 km. This decrease in the percentage difference between the two D_3 values as the urban radius increases is to be expected on the basis of known behavior of point source plumes. Because most large electricity power plants associated with a metropolitan area are located at the edge of the urban area, the spatial configuration chosen for development of D_3 located the tall point source at the urban edge. This configuration is considered to be representative.

Compared with D_2, the third SCA dispersion parameter is even more insensitive to surface roughness. The city is now only downwind of the point source when the wind is coming from the outlying areas, not from over the urban area. Also, the wind must blow over the city a distance of over 100 stack heights (16 km in this case) before a response to surface roughness occurs in the diffusion. These situations preclude the tall stack from being influenced by changes in urban surface roughness.

Sensitivity to Stack Height

The SCA dispersion parameter D_3 is sensitive to the stack height of the high-level point source, but it is relatively insensitive to the other stack characteristics. The response of D_3 to changes in volume flow-rate and exit temperature are similar to the changes shown in Table 4 for D_2. The Briggs plume-rise formula has no term accounting for stack diameter, so there is no sensitivity to stack diameter in this case. The change in D_3 resulting from changes in stack height is much greater than for D_2.

In conjunction with the large sensitivity of D_3 to stack height, there are two main reasons for explicitly providing a stack height adjustment factor in the SCA method for D_3. First, the range of stack heights within the class of high-level point sources is large and data is usually readily available for power plant stack heights. Second, the stack height of electric power stations is often a policy factor in questions of air pollution impacts--stack heights of power plants have been increasing in height because of environmental policies. Stack height adjustment factors for the high-level point source SCA dispersion parameter are given in Table 6 and presented graphically in Figure 17.

Table 6. Stack height adjustment factors for D_3 at given stack heights.

Stack Height (m)	Ratio to Reference Stack Height	High-level Point Source SCA Dispersion Parameter (D_3) Adjustment Factor
80	0.48	3.54
100	0.61	2.48
150	0.91	1.10
165	1.00	1.00
200	1.21	0.79
250	1.52	0.54
300	1.82	0.33

Again, the adjustment factor varies with urban radius; however, this variation with radius is not more than ±3% and is considered negligible for the purposes of the SCA method.

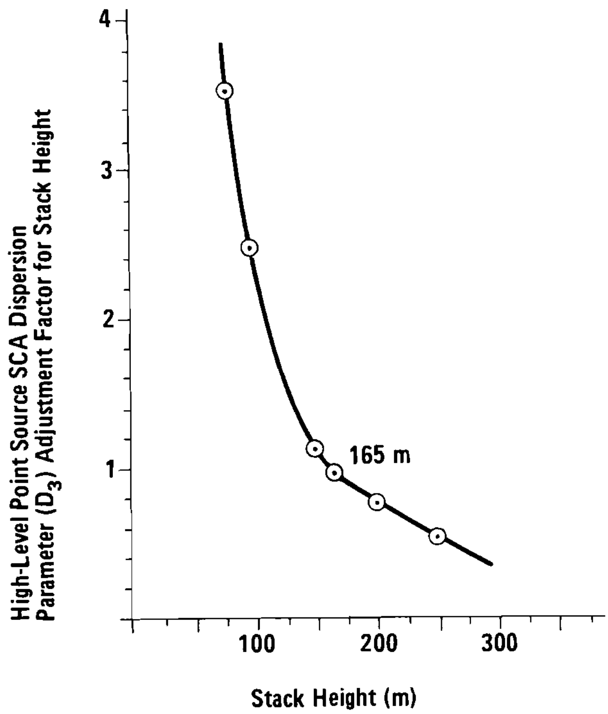

Figure 17. SCA D_3 stack height adjustment factor.

<u>Form of the SCA High-Level Point Source Dispersion Parameter</u>

The curvatures, as a function of radius, of the D_{3km}'s for a given combination of wind speed and atmospheric stability is even more extreme than for the D_{2km}'s. An example is shown in Figure 18 for moderate winds. A very large decrease in the magnitude of several D_{3km}'s occurs as the urban radius decreases. Below a given urban radius, some of the D_{3km}'s are, for all practical purposes, zero. In fact, the D_{3km}'s for stable atmospheric conditions only have a contributing effect to the composite D_3 for an urban radius greater than 30 km, i.e., for most urban areas, stable conditions produce no exposure from tall stacks. Because many of the D_{3km}'s fall away as the urban radius decreases, a rather flat composite D_3 for a typical set of annual meteorological statistics is produced. This may be seen in Figure 19.

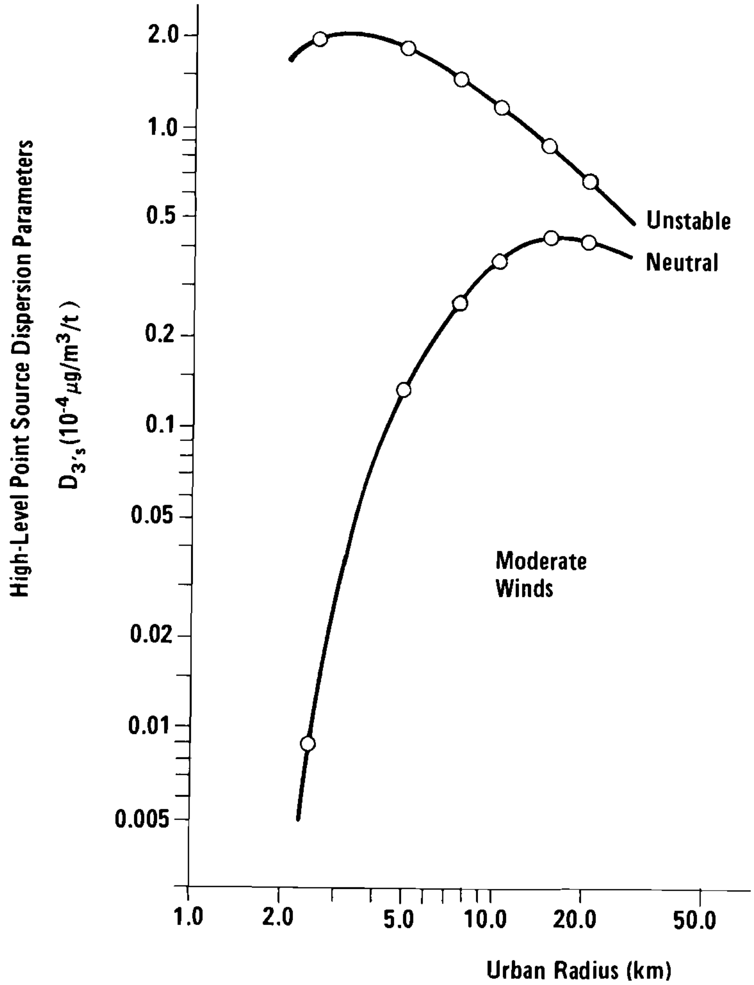

Figure 18. SCA D_{3km}'s as a function of urban radius for moderate winds and all atmospheric stabilities.

<u>SCA Dispersion Kit for D_3</u>

As with D_2, three terms are sufficient to describe the individual D_3's for a given combination of meteorological conditions. The equational form is the same as for D_2:

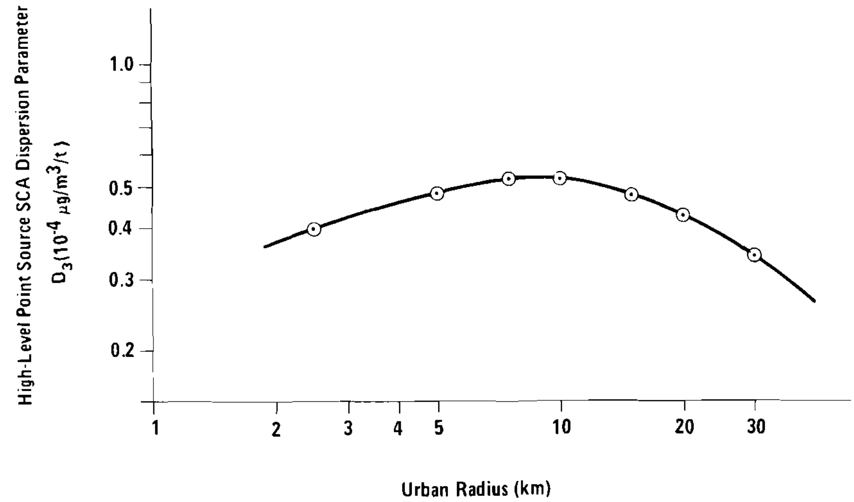

Figure 19. SCA composite D_3 as a function of average urban radius for a typical set of meteorological conditions.

$$\ell n(D_{3km}) = a_{3km} + b_{3km}(\ell nR) + c_{3km}(\ell nR)^2 \qquad (7)$$

where k is the atmospheric stability,

m, the wind speed, and

R, the average urban radius.

For D_3, the set of three coefficients, a_{3km}, b_{3km}, and c_{3km}, form the SCA dispersion kit for the high-level point source SCA dispersion parameter. This kit is presented in Table 7. The stable case is only included for theoretical interest. When the kit is actually being used to derive the composite D_3, the D_{3km}'s for the stable case can be given the value of zero.

A composite D_3 is compared and contrasted to a composite D_2 and D_3 in the next section. Use of the kit for D_3 is demonstrated in Appendix A3. The same meteorological conditions are used to derive a composite D_3 as a function of urban radius as in Appendix A1.

Table 7. High-level point source SCA dispersion kit: D_3.

$$\ell n(D_{3km}) = a_{3km} + b_{3km}(\ell nR) + c_{3km}(\ell nR)^2$$

D: units of 10^{-4} $\mu g/m^3/t$ per unit time

R: units of kilometers

Atmospheric Stability (k)	Wind Speed (m)	SCA Dispersion Kit Coefficients		
		a_{3km}	b_{3km}	c_{3km}
Unstable	Very Low	1.1710	0.8849	-0.2837
	Low	1.0344	0.4271	-0.2301
	Moderate	0.5996	0.3266	-0.2164
	High	0.6470	0.2506	-0.2316
Neutral	Very Low	-30.8007	19.5370	-3.1169
	Low	-13.8196	7.9813	-1.2264
	Moderate	-9.3807	6.2428	-1.1238
	High	-6.2753	4.2501	-0.8205
Stable	Very Low	-18.3797	3.9778	0.0
	Low	-44.5100	20.8940	-2.6537

VI. COMPARISON OF D_1, D_2 and D_3

The SCA dispersion parameters have been formulated, with their SCA dispersion kits, for each of the three emission classes and it has been shown that a minimum of input data is needed to use each SCA dispersion parameter. In addition, the usefulness of the SCA dispersion parameters for long-term policy analysis derives from their distinct differences and their being functions of average urban radius. There are two basic differences between the composite SCA dispersion parameters for the three emission classes--illustrated in Figure 20: the values of the D_i's are distinctly separated and the slopes of the D_i's as a function of average urban radius are different. The composite D_i's of Figure 20 are derived for the annual meteorological statistics given in Appendix A1, using Equation (1) and the SCA dispersion kits. Figure 20, therefore, depicts graphically the three composite D_i's developed in detail in Appendix A.

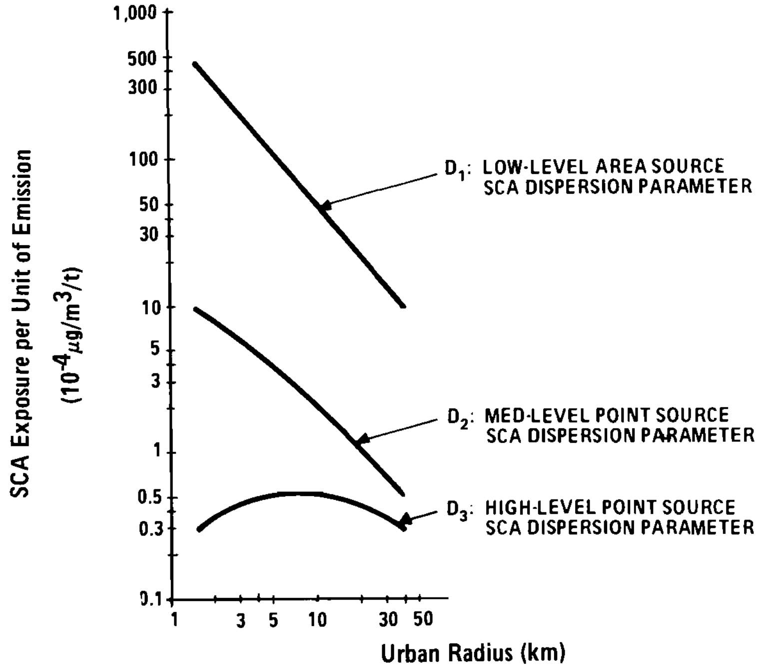

Figure 20. Composite annual SCA dispersion parameters $D_1(R)$, $D_2(R)$ and $D_3(R)$.

The distinct separation of the exposure per unit of emission for each SCA dispersion parameter is important for the consideration of air pollution damages. The differences in exposure can more easily be seen by taking the ratio of the composite D_i's at particular radii. The ratios of the composite D_i's of Figure 20 at radii of R = 2, 6, 10 and 30 km are given in Table 8. The difference between area source exposure per unit of emission and point source exposure per unit of emission (both medium- and high-level) is large and remains large at all urban radii. This is important to know for air pollution damage analysis and thus air pollution control policy analysis. The distinction between the exposures per unit of emissions produced by the two classes of point source emissions is moderate, but still important.

As the average urban radius increases towards urban conglomerations, the distinction decreases between the exposure per unit of emission produced by medium-level point sources and high-level point sources. This is due to the large difference in the slopes of D_2 and D_3 as a function of urban radius. Thus point source emission control strategies might be viewed differently for different city size classes. The fact the D_1 and D_2

Table 8. Ratios between the composite D_i's at different average urban radii.

Average Urban Radius (km)	Ratio of D_1 to D_2	Ratio of D_2 to D_3	Ratio of D_1 to D_3
2	39.0	21.9	854
6	27.3	6.26	171
10	24.1	3.98	96.0
30	20.3	1.99	40.4

are functions of average urban radius also has implications for urban planning. Urban planning recommendations to increase city densities in order to improve services per unit cost or to reduce energy use in, say, personal transportation, could well increase the air pollution exposure per person.

In addition to the contrasts between the composite D_i's, the individual D_{ikm}'s of the SCA dispersion kits provide basic information on some underlying dispersion differences between the three classes of emission sources. For example, for area sources, the meteorological conditions producing the largest exposure per unit of emissions are associated with the stable atmospheric condition; whereas, for high-level point sources, the stable atmospheric conditions produce no effective exposure for urban radii less than 30 km. Although the SCA dispersion parameters can be used individually, much of their policy usefulness is considered to derive from comparing and contrasting them and by using them together, as will be illustrated by the examples given in Section VII.

VII. USING THE SCA METHOD

The previous sections have presented the basic features of the SCA method and have described in detail the three SCA dispersion parameters. This section will describe some ways in which the SCA method has been used to date. In the first part, validation of the SCA method is discussed. In the second part two examples of the use of the SCA method are provided: first, a specific urban sensitivity study and second, a discussion of the use of the method, with selected results, for regional studies. In the final section general comments and conclusions about the use of the SCA method are made.

Validation

Validation of the SCA method is still in the initial stages. It requires detailed emission inventories for urban areas that are divisible into the three classes of SCA dispersion parameters. Because monitoring data is usually not a very good proxy for a spatially averaged exposure over an entire urban area, it is also helpful to have the results of model calculations from dispersion models that have been calibrated for the urban area.

The SCA method has been validated in detail for three cities where emissions inventories were readily available, namely Madison and Milwaukee, Wisconsin (USA) and Vienna, Austria. For the Wisconsin cities detail isopleths from a calibrated dispersion model were also available. For the three cities, the calculated exposure was within 20% of the expected exposure based on monitoring data and within 5% of the expected exposure based on the dispersion model isopleths.

Validation results are shown in Table 9 for Milwaukee, Wisconsin and in Table 10 for Vienna, Austria. The validation compares the SCA exposure with spatially averaged monitoring data (and, for Milwaukee, spatially averaged dispersion model results) in a year for which an official emissions inventory is available. The agreement for both Milwaukee and Vienna is good. The agreement between the SCA exposure and the spatially averaged isopleths of the dispersion model calibrated for Milwaukee are individually good for both the area sources and the combined point sources (the dispersion model results were only available with the point sources combined). The three SCA dispersion parameters appear to provide a reasonable value for the spatially averaged ambient ground-level air pollution concentration (SCA exposure) in an urban area. The SCA dispersion parameters also appear to provide a good assessment of the relative contribution made by each emission source class to the ambient ground-level exposure.

Examples of the Use of the SCA Method

Selected results of two different studies will be briefly presented to illustrate major ways in which the SCA method can be used: analysis of a single urban area and analysis of a region (with many urban areas).

Single Urban Area Analysis

There are certain types of energy/environment questions or policy issues concerning a single urban area for which the SCA method can provide an insight. One such question is the relative human health impact at the urban level for space heating by district heating versus the usual building or dwelling space heat

Table 9. SCA method validation for Milwaukee, Wisconsin (USA) SO_2 comparison, 1973.

	SO_2 Emissions* (t)	SCA Method Exposure ($\mu g/m^3$)	Dispersion Model** Exposure ($\mu g/m^3$)	Monitoring Data* ($\mu g/m^3$)
Area Sources (D_1) Transportation	743	18.7	17.3	N.A.
Residential & Commercial	8,605			
Point Sources (D_2) Industry	7,486	1.6	7.7	
Power Plants (D_3)	139,800	6.1		
Subtotal	156,634	26.4	25.0	
Background		5.0	5.0	
TOTAL		31.4	30.0	35-40

N.A. Not Applicable
* Source: [17]
** Source: [18]

Table 10. SCA method validation for Vienna, Austria SO_2 comparison, 1974.

	SO_2 Emissions* (t)	SCA Method Exposure ($\mu g/m^3$)	Monitoring Data** ($\mu g/m^3$)
Area Sources (D_1) Residential & Commercial	14,256	60.5	N.A.
Point Sources (D_2) Industry	11,462	2.1	
Power Plants (D_3)	14,877	0.8	
Subtotal	40,595	63.4	
Estimated Background		2-5	
TOTAL		65-68	69

N.A. Not Applicable
* Source: [19]
** Source: [20]

furnace. Often such analysis of a single urban area consists of a detailed look at a particular issue for a particular urban area after a regional analysis has been completed. This was the procedure followed in this example.

During regional energy/environment analysis, performed at IIASA [21], of an industrial area in the German Democratic Republic, it became clear that the use of district heat had a strong influence on the local levels of air pollution exposure. Because it was foreseen that in the future coal would be primarily burned to provide space heat (for economic reasons including national balance of payments), GDR policy makers developed a strong interest in the issue of air pollution and the use of district heat for providing space heat. A sensitivity study for the main city in the area was designed in order to look at the changes in air pollution exposure that might result from a maximum possible penetration of district heating in the residential sector by the year 2025. The results of this sensitivity study are shown in Figure 21. The net effect is that the use of district heat in plants (whose stacks are similar to industrial stacks) can reduce the local exposure to the city's own residential SO_2 emissions by a factor of 10 if normal coal furnaces are nearly completely replaced by district heating plants. District heat is now being studied as a serious option for meeting space heat demands in the southern GDR region. Such first-cut evaluations are one of the purposes of the SCA method.

Regional Analysis

The SCA method was originally designed for long term regional analysis. Its intent was to provide a simplified algorithm for handling air pollution exposure in the many urban areas that are contained within in a region. The regional analysis is essentially an aggregation of individual urban area analyses with the rural exposure (background concentration) carried along on a conservation of mass basis or calculated by long-range transport models. An example of a regional study using the SCA method is the LIASA Austrian Regional Energy/Environment Study [4]. Selected results will be presented from this study to illustrate the type of regional analysis the SCA method can provide.

There are several steps in a regional analysis that are exogenous to the SCA method. The most important of these are: defining the level of disaggregation of the urban areas to be modeled, associating emissions with each urban area and each rural area, defining the emissions in terms of the three SCA dispersion parameter classes, calculating the average urban radius and accounting for urban growth along with population growth, and calculating a background concentration to be added to the urban exposure calculated by the SCA method. The approaches that were used for these steps in the analysis of the Austrian case study are discussed in [5].

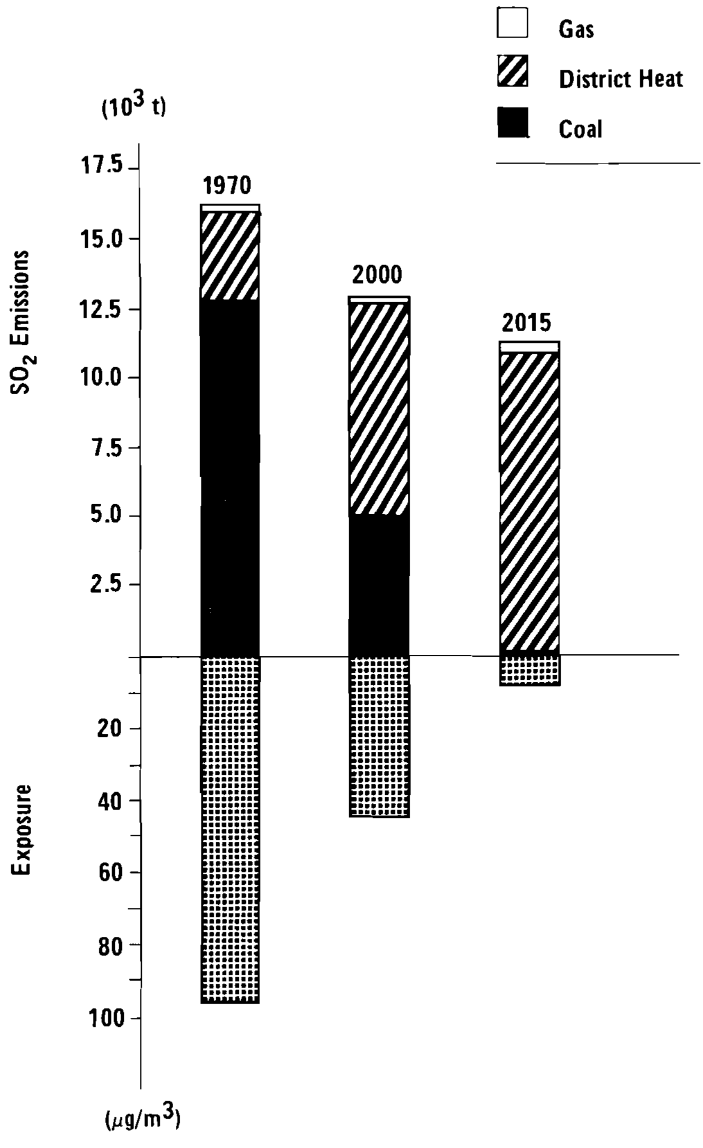

Figure 21. Main city sensitivity of SCA exposure due to residential sector SO_2 emissions as their source changes in an industrial area in the GDR.

One note of caution is necessary for the first step above. For cities aggregated into size classes, the collective exposure for the aggregated set of cities will be underestimated; that is, the average exposure, based on average city characteristics, multiplied by the population in that city size class is lower than the results obtained by calculating the exposure for each city, multiplying the city population and then summing. The degree of underestimation is related to the standard deviation within the aggregated set of urban areas of the product of exposure times population for each urban area. Taking this aggregation effect into account, the need for detail can be reduced to a manageable level for large regional studies.

To demonstrate the type of regional analysis at the policy level that the SCA method can provide, one sensitivity study from the Austrian case study, will be briefly presented; a more complete description is available in [4]. The sensitivity study was directed towards the setting of SO_2 emission standards, an important environmental issue in Austria. Three stages of SO_2 emission standards were defined and the effectiveness of the assumed SO_2 standards in terms of the reduction in health impact produced by each stage was analyzed. The three stages of standards were:

- Stage 1: Complete implementation by 1981 of desulfurization of oil to new limits set by the Austrian ministry of health and environment.
- Stage 2: For all emission sources, implementation, starting in 1985 and completed by 2000, of the present US emission standard of 2.16 kg of $SO_2/10^6$ kcal on all emission sources.
- Stage 3: For all point sources, implementation starting in 2000 and completed by 2015, of the more stringent US standards anticipated for 2000 of 1.08 kg of $SO_2/10^6$ kcal.

The effects of the standards on emissions are shown in Figure 22. Each stage of the standards has a large impact on the total SO_2 emissions. With the SCA method the effects on human health impact, measured in person days lost (PDL)*, can conveniently be studied. The SCA exposure was input to a human health impact model, giving the resulting health impact in terms of PDL. The effects of the standards on human health impact are shown in Figure 23. Each stage of the SO_2 regulations has a decreasing influence on human health impact.

*The concept of PDL combines different types of accidents and sickness into one measure. Each type of accident or sickness has on the average, a characteristic number of days of meaningful interaction per individual that are lost to society. For example, if workers injured in a particular type of industrial operation lose an average of 30 days of work per injury, this represents 30 PDL per injury.

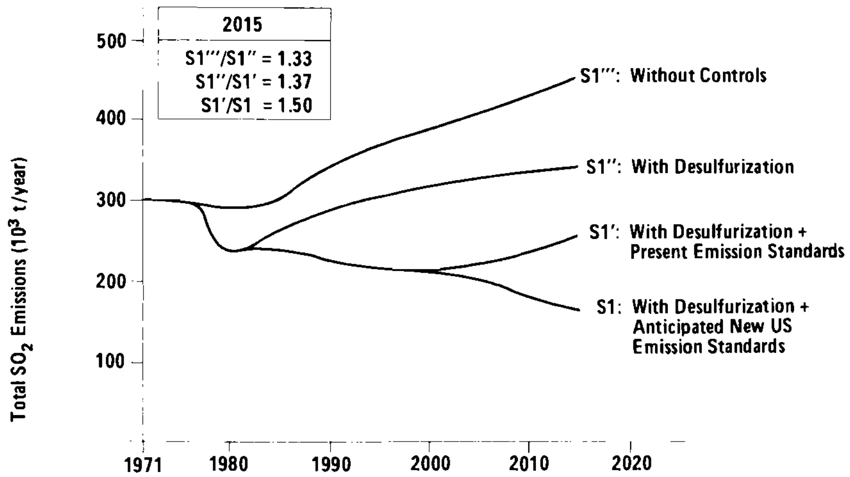

Figure 22. Sensitivity of SO_2 emissions in Austrian case study to assumed emission standards.

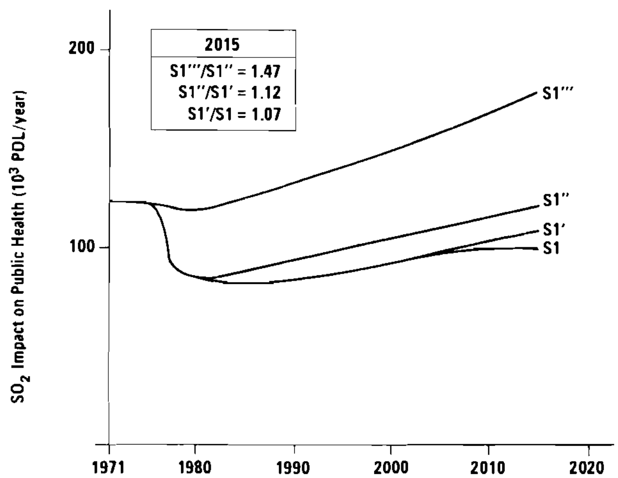

Figure 23. Sensitivity of health impact in Austrian case study to assumed emission standards.

The reduction in influence of the SO_2 emission standards is because residential and commercial-service emissions (SCA dispersion class 1) are only slightly affected by stage 2 of the SO_2 standards and completely unaffected by stage 3 of the standards. As pointed out in Section VI, these low-level emissions more strongly affect exposure in urban areas per unit of emissions than industrial or electric power plant sources of emissions. The share of the urban exposure that is affected by stages 2 and 3 of the emission standards is small and declining, thus the reduction in human health impact from each successive stage of standards diminishes.

This sensitivity analysis provides an indication of the type of policy analysis within long-range regional studies that can be made with the SCA method. Implications of long-range decisions can be scrutinized with a minimum of data needs for the entire region and also for important urban centers; different scenarios can be easily defined, run, and analyzed with the SCA method. It is important to stress that the method must be used in the proper context. An understanding of the method's strengths and weaknesses is essential when it is used as an aid to give insights to policy questions. Some comments on these strengths and weaknesses are presented in the next section.

Concluding Comments

As previously stated, the SCA method is primarily designed for long-range regional analysis in which there are important urban population concentrations and in which urban impacts are important. In this context, several common questions have arisen during the course of presenting and using the SCA method. It is considered worthwhile to comment on many of these questions because the comments will provide further background to the limits and adaptability of the method.

Two common questions arise in the realm of atmospheric dispersion, wind-rose effects and terrain or geographic effects. The SCA dispersion parameters were developed assuming a uniform wind rose. Wind rose effects are not important for D_1, can be important for D_2 [8] and are most likely important for D_3. However, for a given city, the relative changes in air pollution exposure as a function of time and scenario will be properly represented by the SCA dispersion parameters. Small cities or towns may have greatly different point source location patterns; for regional studies these effects would be expected to average out. Wind-rose effects could be more important for larger cities, when different large cities are being compared or when a large city has an unusual concentration of point sources in one or two locations. These factors can be accounted for by weighting the meteorological statistics with wind-rose statistics to produce a weighted set of statistics for use in producing a weighted D_2 and D_3 for those cities.

Many terrain and geographic effects will be embedded in the meteorological statistics. Inversion effects for cities in valleys or bowls will be contained in a larger frequency of occurrence of stable atmospheric condition. Given that relevant meteorological statistics are used, the SCA dispersion parameter built from the SCA dispersion kit will automatically reflect these terrain effects. The SCA dispersion parameter is less reliable when a significant fraction of the population lives on the sides as well as the bottom of the bowl.

The most important limitation of the approach has already been mentioned; the SCA method is designed to analyze the short-range urban impact of nonreacting pollutants. When the causal agents of the impacts are chemical reaction products, then it is necessary to introduce exogenous assumptions in order to model the urban exposure. In such a case, the SCA method should be supplemented by a long-range transport calculation to balance the analysis of scenarios and of policy options. For slowly reacting species such as SO_2, both short- and long-range methods should be employed. For rapidly reacting species, such as photochemical smog, the SCA method may not be the proper vehicle for analysis. If it is an acceptable vehicle for given policy considerations, then the exogenous assumptions will be important and long-range transport will most likely be a minor factor.

The SCA dispersion parameters D_1 and D_2 are sensitive to the definition of the urban radius. The question "where does a city end" always produces discussion in urban geography. For this reason, it is very important that a consistent definition be used throughout for a given region and scenario--a strength of the method is assessing relative changes. Where possible, detailed urban and air pollution monitoring data can be used for calibration checks. When there is a question of conglomerations of urban areas, judgment must be used. One rule of thumb is that exposures due to area sources decrease very rapidly at a city "edge" and a 1 km separation between urban areas can be distinguished for area sources. A judicious use of background concentration estimations together with assumptions of conservation of mass and the use of individual SCA dispersion parameters is probably the best way to treat this difficult question.

One concern raised by other modelers is that too much has been averaged away, but we are convinced that this is not the case. The simplification in the SCA method comes from a judicious use of detailed, complex dispersion models. The SCA dispersion parameters embody in a compact form the essential features of urban dispersion. As previously discussed, an additional refinement of the spatial distribution of exposure does not add enough traditional information for strategic planning analysis at the regional level, given present damage function uncertainties, to warrant the burden of the extra detail required to use a more refined method.

The SCA method is best used as a tool for first-cut long-term policy option analysis. The method can be used to compactly characterize air pollution exposure at the urban level and compare differences in the ground-level exposure produced by the major emission classes with a minimum input of meteorological and emissions data. The SCA method is best used in analyses using simulation, either at the regional level (involving many urban areas) or for individual urban area studies. The case studies conducted to date with the SCA method suggest that it can give valuable insight in real policy analysis. The SCA method can be a useful and usable tool for air pollution impact analysis when used in the proper context.

Appendix A

Example Derivation of SCA Dispersion Parameters Using the SCA Dispersion Kits

Presented in this Appendix is an example of the derivation of the SCA dispersion parameters for a typical set of meteorological statistics. This example is intended to provide, for each of the three classes of SCA dispersion parameters, a set of results that can be used as a double-check by a person using the SCA method. The typical set of meteorological statistics for use in the example is given in Table A1. The frequency factor expresses the fraction of the time (relative to 1.0) that a particular wind speed class occurs together with a particular atmospheric stability class. For this example, not all possible wind speeds are present, but the frequency factors sum to unity (with some roundoff error). These are annual frequency factors; therefore, the composite SCA dispersion factor that is developed will calculate an annual SCA exposure and the emissions used together with the SCA dispersion parameter must be the total annual emissions.

Table A1. Example meteorological statistics: frequency of the different combination of wind speed and atmospheric stability.

Atmospheric Stability	Wind Speed	Frequency Factor
Unstable	Very low	0.034
	Low	0.031
	Moderate	0.051
Neutral	Very low	0.025
	Low	0.059
	Moderate	0.172
	High	0.328
Stable	Very low	0.108
	Low	0.194

DERIVATION OF D_1: LOW-LEVEL AREA SOURCE SCA DISPERSION PARAMETER

The SCA dispersion parameter D_1 for particular urban radius, R_0, is calculated by multiplying each D_{1jk} for the given radius by the corresponding frequency factor, FF_{jk}, for atmospheric stability j and wind speed k, i.e.

$$D_1(R_0) = \sum_{jk} FF_{jk} D_{1jk}(R_0) \quad , \tag{A1}$$

where

$$D_{1jk}(R_0) = \exp\{a_{1jk} + b_{1jk} \ln R_0\} \quad , \tag{A2}$$

where a_{1jk} and b_{1jk} are the SCA dispersion kit coefficients. For example,

$$D_{111}(10\text{km}) = 19.201$$

$$FF = 0.034 \quad .$$

Thus, the first term in the summation in Equation (A1) is equal to 0.6528. Continuing this example for each of the frequency factors of Table A1, we calculate

$$D_1(6\text{km}) = 87.62 \times 10^{-4} \mu g/m^3/\text{ton}* \quad ,$$

$$D_1(10\text{km}) = 48.66 \times 10^{-4} \mu g/m^3/\text{ton} \quad .$$

To obtain D_1 as a general function of urban radius, R, D_1 must be computed as in Equation (A1) for several values of urban radius and a curve fitted to the results. Using the frequency factors of Table A1, ten values of D_1 were calculated for urban radii ranging between the two end points of 2 and 30 km (here only 4 significant figures were kept for the SCA dispersion kit coefficients). A curve was fitted through the 10 values of D_1, and the coefficients a_1 and b_1 for Equation (A3) were determined.

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*In this Appendix tons will always mean tons per annum.

$$\ell n D_1(R) = a_1 + b_1 \times \ell n R \quad . \tag{A3}$$

The coefficients are:

$$a_1 = 6.5628$$

$$b_1 = -1.1524 \quad .$$

With these coefficients D_1 can be calculated for any urban radius. Just for interest and to give some concrete numbers, we can compare the D_1 computed by Equation (A3) with the D_1 computed by Equation (A1). This comparison is given in Table A2. It is interesting to note that although each of the D_{1jk}'s is a straight line when plotted on a log-log plot, D_1 is no longer altogether straight; a straight line fit is still reasonable, however.

Table A2. Comparison of SCA dispersion parameters (D_1) calculated for individual urban radii with those calculated from the fitted curve coefficients.

Urban Radius (km)	D_1 Individual Cases ($10^{-4}\mu g/m^3/t$)	D_1 Fitted Curve ($10^{-4}\mu g/m^3/t$)
2	335.3	318.6
6	87.62	89.85
10	48.66	49.87
20	22.65	22.44
30	14.71	14.06

DERIVATION OF D_2: MEDIUM-LEVEL POINT SOURCE SCA DISPERSION PARAMETER

The SCA dispersion parameter D_2 for a particular urban radius, R_0, is calculated in the same manner as D_1, i.e., as given by

Equation (A1). For D_2, however, D_{2jk} is given by the following equation:

$$D_{2jk}(R_0) = \exp\{a_{2jk} + b_{2jk}\ln R_0 + c_{2jk}(\ln R_0)^2\} \quad , \qquad (A4)$$

where a_{2jk}, b_{2jk}, and c_{2jk} are the SCA dispersion kit coefficients for atmospheric stability j and wind speed k. Again, using the frequency factors of Table A1, we calculate

$$D_2(6km) = 3.28 \times 10^{-4} \mu g/m^3/ton \quad ,$$

$$D_2(10km) = 2.07 \times 10^{-4} \mu g/m^3/ton \quad .$$

To obtain D_2 as a general function of urban radius, R, the same procedure was followed as with D_1 above, computing 10 values of D_2 at various urban radii. In this case, a curve of the form given in Equation (A5) was fitted through the 10 values of D_2 and the coefficients a_2, b_2, and c_2 were determined.

$$\ln D_2(R) = a_2 + b_2\ln R + c_2(\ln R)^2 \quad . \qquad (A5)$$

The coefficients are:

$$a_2 = 2.6080$$

$$b_2 = -0.6961$$

$$c_2 = -0.0526 \quad .$$

As with D_1 we compare the D_2 computed with these coefficients with the D_2 computed by an equation in the form of A1. This comparison is shown in Table A3. Interestingly, although there is strong curvature as a function of urban radius in some of the D_{2jk}'s when plotted on a log-log graph (see Figure 17), this feature is not very noticeable in D_2; in fact, between 2 km and 30 km, D_2 can also be approximated with two straight line segments on a log-log plot, the discontinuity in slope occurring at about 8 km.

Table A3. Comparison of SCA dispersion parameter (D_2) calculated for individual urban radii with those calculated from the fitted curve coefficients.

Urban Radius (km)	D_2 Individual Cases ($10^{-4}\mu g/m^3/t$)	D_2 Fitted Curve ($10^{-4}\mu g/m^3/t$)
2	8.215	8.169
6	3.284	3.294
10	2.074	2.068
20	1.058	1.052
30	0.6874	0.6924

DERIVATION OF D_3: HIGH-LEVEL POINT SOURCE SCA DISPERSION PARAMETER

The SCA dispersion parameter D_3 for a particular urban radius, R_0, is calculated in the same manner as D_2. The equation for D_{3jk} has the same form as Equation (A4) with the subscript 2 replaced by the subscript 3. Using the frequency factors of Table A1 for the derivation of $D_3(R_0)$ for the same radii as the above examples,

$$D_3(6\text{km}) = 0.530 \times 10^{-4}\mu g/m^3/t$$

$$D_3(10\text{km}) = 0.536 \times 10^{-4}\mu g/m^3/t$$

The same procedure as for D_2 is followed to obtain D_3 as a general function of urban radius. For the fitting of Equation (A6) through the 10 values of D_3,

$$\ell nD_3(R) = a_3 + b_3 \times \ell nR + c_3 \times (\ell nR)^2 \quad , \qquad \text{(A6)}$$

the resulting coefficients a_3, b_3, and c_3 are;

$$a_3 = -1.4640$$

$$b_3 = 0.8362$$

$$c_3 = -0.2105 \quad .$$

Table A4, for selected urban radii, shows the comparison of D_3 computed with these coefficients with D_3 computed by an equation of the form of Equation (A1). As stated earlier, one of the reasons for this comparison is to provide some example numbers for the purposes of a check.

Table A4. Comparison of SCA dispersion parameters (D_3) calculated for individual urban radii with those calculated from the fitted curve coefficients.

Urban Radius (km)	D_3 Individual Cases (10^{-4} $\mu g/m^3/t$)	D_3 Fitted Curves (10^{-4} $\mu g/m^3/t$)
2	0.3952	0.3732
6	0.5084	0.5264
10	0.5365	0.5194
20	0.4537	0.4280
30	0.3212	0.3479

The three composite D_i's calculated in this Appendix are also shown graphically in Figure 20 in the test for further reference.

Appendix B

Point Source Characteristics Used for the Development of the SCA Point Source Dispersion Parameters

REFERENCE SET OF MEDIUM-LEVEL POINT SOURCES

	Stack and Stack Gas Characteristics			
	Height (m)	Top Diam. (m)	Vol. Flow (m^3/s)	Exit Temp. (K)
1.	79	3.9	93.6	505
2.	24	0.8	38.7	322
3.	23	1.4	154.8	450
4.	21	1.5	46.5	496
5.	21	1.5	46.5	496
6.	46	1.9	61.9	588
7.	53	1.2	23.2	505
8.	8	1.2	7.7	422
9.	12	1.2	17.0	593
10.	46	1.9	61.9	588
11.	53	1.2	23.2	505
12.	12	1.2	17.0	593
13.	23	1.1	51.1	444
14.	36	1.2	12.4	547
15.	36	1.2	12.4	547
16.	15	0.9	3.3	476
17.	23	1.5	26.0	427
18.	30	1.2	11.8	339
19.	30	1.2	11.8	339
20.	32	2.1	30.4	455
21.	32	2.1	30.4	455
22.	32	2.1	30.4	455
23.	58	1.2	33.0	346
24.	44	2.7	17.3	450

REFERENCE FOSSIL ELECTRICITY POWER PLANT

	Stack and Stack Gas Characteristics			
	Height (m)	Top Diam. (m)	Vol. Flow (m^3/s)	Exit Temp. (K)
1.	165	5.3	679	389

Appendix C

Description of Air Pollution Dispersion Models Used in Formulation of SCA Dispersion Parameters

AREA SOURCE DISPERSION MODEL

The basic diffusion equation used in the model is presented first and the meteorological parameters to develop a vertical wind profile which takes surface roughness into account and a vertical diffusivity profile follow. A more detailed description of this model can be found in [9].

Dispersion Model for Area Sources

This model computes ambient air concentrations of air pollutants due to emissions from area sources of chemically non-reactive pollutants.

To make the problem conveniently tractable, commensurate with readily observable meteorological data, and yet physically realistic, we have assumed that the wind field is uniform, varying only with height above the ground, and that diffusion parallel to the wind may be neglected in comparison to the advective transport. Consider a fixed rectangular coordinate system with the x-axis oriented along the wind vector u, the y-axis oriented cross-wind, and the z-axis oriented vertically upward. For a nonreacting pollutant species C(x,y,z) with an emission source distribution S(x,y,z) the diffusion equation becomes

$$u \frac{\partial C}{\partial x} - K_y \frac{\partial^2 C}{\partial y^2} - \frac{\partial}{\partial z} (K_z \frac{\partial C}{\partial z}) = S \quad . \tag{C1}$$

The wind speed u(z) and the eddy diffusivities K(z) are obtained from the Monin-Obkuhov similarity theory as described in the next section. Boundary conditions specify that the pollutants do not penetrate the top of the mixing layer (inversion height) or diffuse laterally outside the grid. The background concentration at the up-wind edge of the region must be specified, as well as the initial concentration array within the region.

Equation (C1) with boundary and initial conditions is solved numerically by means of a first order fully implicit finite difference technique. This method is numerically stable for any step size and for this application the numerical errors are small.

Meteorological Parameters

The wind and eddy diffusivity profiles depend on the stability of the atmosphere. In terms of boundary layer notation, atmospheric stability may be characterized by the parameter L [23].

$$L = \frac{u_*^3 \rho c_p T}{kgH} \quad , \tag{C2}$$

where u_* is the so-called friction velocity, H is the net heat flux to the ambient air density, c_p is the specific heat, T is the temperature, k is Karman's constant (= 0.4), and g is the gravitational constant. L has the units of length.

It is convenient to introduce a drag coefficient, c_g, based on the geostrophic wind, u_g, such that,

$$u_* = c_g u_g \quad . \tag{C3}$$

The geostrophic drag coefficient has been shown to be a function of the surface Rossby number ($R_0 = u_g/Z_0 f$) and L, where f is the Coriolis parameter of the earth and Z_0 is the surface roughness. For a neutral atmosphere, Lettau [24] suggests the following empirical relationship

$$c_g = 0.16/[\log_{10}(R_0) - 1.8] \quad . \tag{C4}$$

To account for the effects of stratification on the drag coefficient we have taken:

- Unstable flow: $c_g = 1.2 c_g(\text{neutral})$,
- Slightly unstable flow: $c_g = 0.8 c_g(\text{neutral})$,
- Stable flow: $c_g = 0.6 c_g(\text{neutral})$.

The surface roughness, Z_0, is calculated according to the relationship of Lettau [12] and given in Equation (2) of the text.

The above information is sufficient to calculate the wind profile and the eddy diffusivity profile within the surface layer of the atmosphere. The equations used are summarized in Table C1.

Table C1. Wind and diffusivity profiles used in the area source dispersion model.

Stability		Vertical Distance	Wind Speed u	Eddy Diffusivity K_y, K_z
Within Surface Layer	Neutral	$0 < z \leq z_{SL}$	$\frac{u_*}{0.4} \ \ln\left(\frac{z + z_0}{z_0}\right)$	$K_z = 0.4u_* z$ $K_y = 5K_z$
	Stable	$0 < z \leq z_{SL}$ AND $0 < z \leq L$	$\frac{u_*}{0.4}\left[\ln\left(\frac{z + z_0}{z_0}\right) + \frac{5.2z}{L}\right]$	$K_z = 0.4u_* z/\left(1 + \frac{5.2}{L}z\right)$ $K_y = 6K_z$
		$L < z \leq z_{SL}$	$\frac{u_*}{0.4}\left[\ln\left(\frac{z + z_0}{z_0}\right) + 5.2\right]$	$K_z = 0.4_* z/6.2$ $K_y = 6K_z$
	Unstable	$0 < z \leq z_{SL}$ OR $0 < z \leq \lvert 2L \rvert$	$\frac{u_*}{0.4}\left[2(\tan^{-1}x - \tan^{-1}x_0) + \ln\left(\frac{x - 1}{x_0 - 1}\right) - \ln\left(\frac{x + 1}{x_0 + 1}\right)\right]$ $x = [1 - 15(z + z_0)/L]^{1/4}$ $x_0 = [1 - 15z_0/L]^{1/4}$	$K_z = 0.4u_* z\left(1 - \frac{15z}{6}\right)^{1/4}$ $K_y = 2K_z$
Above Surface Layer	Neutral	$z_{SL} < z \leq z_m$	$(u_g - u_{SL})\left(\frac{z - z_{SL}}{z_m - z_{SL}}\right) + u_{SL}$	$K_z = 0.4u_* z_{SL}$ $K_y = 5K_z$
	Stable	$z_{SL} < z \leq z_m$	$(u_g = u_{SL})\left(\frac{z - z_{SL}}{z_m - z_{SL}}\right) + u_{SL}$	$K_z = 0.4u_* L$ $K_y = 6K_z$
	Unstable	$z_{SL} < z \leq z_m$ OR $\lvert 2L \rvert < z \leq z_m$	$(u_g - u_{SL})\left(\frac{z - z_{SL}}{z_m - z_{SL}}\right) + u_{SL}$	$K_z = 160u_*^2\left(1 - \frac{6000u_*}{L}\right)^{1/4}$ $K_y = 2K_z$

Above the surface layer the wind profile is calculated using a linear relationship and the eddy diffusivity is assumed constant with height shown in Table C1.

POINT SOURCE DISPERSION MODEL

The basic diffusion equations used in the model are presented in the section below together with the form of the vertical wind profile equation used to convert wind speed measure at 10 meters to wind speed at the stack height. In the next section two plume-rise formulas are given: Moses and Carson's for medium-level point sources and Brigg's for high-level point sources. A more detailed description of this model can be found in [13], although this model is a fairly standard Gaussian plume type of model.

Dispersion Model for Point Sources

This model calculates on a seasonal or an annual basis the ground-level concentration of a nonreacting air pollutant due to a set of point sources. On a short term basis the concentration of pollutants in the plume exhibit a Gaussian distribution about the effective centerline of the plume. However, on a long term basis (of interest here) the concentration may be considered uniform laterally within a pie-shaped sector due to the random fluctuation of the wind velocity vector. When the wind vector falls outside the sector--taken to be 22.5°--the concentration is assumed to be zero. Vertical diffusion is determined by a Gaussian dispersion coefficient. When this coefficient is large compared to the mixing height, trapping occurs and the concentration is eventually uniform within the sector both laterally and vertically.

By integrating the standard Gaussian plume equation [25] in the y-direction we have the basic long-term dispersion equation which is valid up to the distance x_m, where x_m is defined by [26],

$$z_m = 2.15\sigma_z x_m \quad ,$$

where z_m is the mixing height, and σ_z, the Gaussian dispersion coefficient.

For interaction of the plume with the ground, but not the mixing height, the concentration for one set of meteorological conditions from one source to one receptor is,

$$C_A = \frac{\sqrt{2/\pi}\ nQ}{2\pi u \sigma_z x} \exp\left(-\frac{h^2}{2\sigma_z^2}\right) \qquad \text{for } x \le x_m \quad . \tag{C5}$$

For the trapping due to the mixing height above the plume, an additional integration is carried out in the z-direction and the concentration is

$$C_M = \frac{nQ}{2\pi u z_m x} \qquad \text{for } x \geq 2x_m \quad . \tag{C6}$$

For the intermediate or transition case a linear interpolation is assumed so that,

$$C_T = \frac{nQ}{2\pi u x}\left[\frac{B}{\sigma_z} - \left(\frac{B}{\sigma_z} - \frac{1}{z_m}\right)\left(\frac{x}{x_m} - 1\right)\right] \qquad \text{for } x_m < x < 2x_m \tag{C7}$$

where

$$B = \sqrt{2/\pi}\ \exp\left(-\frac{h^2}{2\sigma_z^2}\right) .$$

In practice the wind speed at stack height should be used in Equations (C5) to (C7). The wind speed at stack height is greater than at the recording height (normally 10 m) because of boundary layer effects, and this was taken into account as follows [25],

$$u = u(\text{measured})\left(\frac{h_s}{10}\right)^{p_j} ,$$

where h_s is the stack height in meters

$p = 0.2$ for stabilities A, B, C, D; 0.5 for E, F.

Before the equations are complete, expressions for the dispersion coefficient, σ_z, and the effective stack height, h, described in the next section, must be obtained. The following expression was used for the dispersion coefficients [26],

$$\sigma_z(L) = 1000a(L)\left|\frac{x}{1000}\right|^{b(L)} , \tag{C8}$$

where σ_z and x are in meters, and the following values are used for a and b:

	Rural		Urban	
Stability	a	b	a	b
A	0.45	2.1	0.63	1.4
B	0.11	1.1	0.34	1.28
C	0.061	0.92	0.169	1.043
D	0.033	0.60	0.124	0.724
E	0.023	0.51	0.0485	0.581
F	0.015	0.45	0.0485	0.581

Plume-Rise Formulas

Plume-rise formulas calculate the plume rise, DH, given the stack diameter, the exit velocity and exit temperature of the plume, and the ambient temperature and the stability of the atmosphere. The heat flux, QH, from the stack (Kcal/s) is defined as

$$QH = QV \frac{(T_s - T_a)}{T_a} \times \text{constant} \quad , \qquad (C9)$$

where QV is the volume flow rate

T_s, the stack exit temperature

T_a, the ambient temperature, and the

constant = 84.88 kcal/m^3.

Which of the two plume-rise formulas to use is determined by the magnitude of the heat flux, QH. When QH is larger than 5000 kcal/s then Brigg's formula is used.

Moses-Carson

Define

$$VS = \frac{QV}{\pi(D/2)^2} \quad , \qquad (C10)$$

where D is the stack diameter in meters.

Then for *unstable atmosphere*

$$DH = 2(3.42VS\ D + 10.53\sqrt{QH}) \quad , \qquad (C11)$$

neutral atmosphere

$$DH = 2(0.35VS\ D + 5.41\sqrt{QH}) \quad , \qquad (C12)$$

stable atmosphere

$$DH = 2(-1.04VS\ D + 4.58\sqrt{QH}) \quad . \qquad (C13)$$

<u>Brigg</u>

Neutral and unstable atmosphere

$$DH = 2.5(QH^{1/3}H^{2/3}) \quad , \qquad (C14)$$

where H = stack height in meters ,

stable atmosphere

$$DH = 2.96\left(\frac{QH}{0.0277}\right)^{1/3} \quad . \qquad (C15)$$

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