Influential Receptors in Targetted Emission Control Strategies

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Preface

The Regional Acidification INformation and Simulation (RAINS) model was originally developed to simulate effects of control strategies of acid deposition. Recently, we started to extend RAINS with an optimization mode which allows a user of the model to investigate receptor-oriented rather than source-oriented policies. Applied to Europe which in RAINS is subdivided in about 600 areas, an optimization demands large computer resources. In order to be able to perform the optimization on a personal computer, the problem size should be reduced considerably.

Stuart Batterman from Texas A&M University (USA) who joined the Acid Rain Project for short periods in 1986 and 1987 has found an ingenious way to cope with the problem size. In this paper he reports on his method and shows several examples of use of the method of "influential receptors".

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Abstract

Emission abatement strategies which are targetted on environmental goals may provide cost-effective alternatives to flat-rate, source-oriented policies. It is not a trivial matter, however, to develop targetted strategies. Such strategies may require the numerical optimization involving large numbers of variables and constraints. These problems demand large computer resources. Moreover, the optimization process itself is likely to be obscure for all but the most technically competent decision-makers.

In this paper, several techniques are presented which identify the receptors locations which influence the outcome of targetted emission abatement strategies. As only such "influential" receptors are needed in optimization problems, their identification may permit a dramatic reduction in the computational burden. These receptors also allow a more direct interpretation of the optimization problem. After developing these filters, influential receptors are identified for several policies related to the reduction of sulfur deposition in Europe.

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1. INTRODUCTION

This paper describes an approach to identify receptor locations which influence the outcome of targetted emission abatement strategies aimed at controlling acidic deposition. These "influential" receptors define the smallest, but entirely sufficient set of receptors required for consideration in optimization problems. By using only influential receptors, the number of receptors modeled in targetted emission control policies may be greatly reduced, thus enabling a commensurate decrease in the computational burden. The identification of these receptors also provides insight into the factors which influence the solution of the optimization problem. These filters have been incorporated into the optimization module of the Regional Acidification INformation and Simulation Model (RAINS) (Alcamo *et al.*, 1987).

Chapter 2 provides some background for targetted control policies. Chapter 3 presents the mathematical definition of the problem of identifying influential receptors, suggests a solution approach, and extends this technique to encompass spatially varying receptor sensitivity and policy constraints. In Chapter 4, the influential receptors in Europe are found using the EMEP model and several targets for sulfur deposition. Chapter 5 discusses the application of these results.

2. BACKGROUND

Environmental impacts first attributed to long range transport of air pollutants occurred in relatively few and well defined areas, such as the Black Forest, southern Finland and Sweden in Europe, and the Adirondacks in North America. Later research indicates that transboundary air pollutants may cause increased acidity and environmental impacts over a much broader, continental scale. Impacts of concern include lake acidity, forest damage, accumulation and release of toxic metals in soil and drinking water, and materials damage in the constructed environment.

In recognition of the adverse effects of acidic deposition, national and international efforts to reduce emissions of precursor pollutants have begun. In Europe, the Protocol to the Convention on Long-Range Transboundary Air Pollutants (1986) states a goal of reducting sulfur emissions by at least 30% from 1980 levels. These reductions are to be achieved by 1993. This uniform or "flat-rate" reduction constitutes a "source-oriented" emission abatement strategies.

2.1. Targetted emission abatement strategies

In contrast to source-oriented strategies, "receptor-oriented" or "targetted" emission abatement strategies are focussed directly on environmental goals. These strategies may achieve environmental targets efficiently by coordinating emission reductions among the major emittors of pollutants. By linking mathematical models of pollutant emissions, abatement control costs, atmospheric transport and environmental impacts, control strategies may be designed which are both more economical and more environmentally beneficial than source-oriented strategies. This approach has been used for North America by Ellis *et al.* (1985), Fortin and McBean (1983) and Morrison and Rubin (1985), and for Europe by Batterman *et al.* (1986), Hordijk (1986), and Amann *et al.* (1987). Similar policies have been suggested for minimizing control costs of emission abatement on a local scale (Kohn, 1982).

Batterman *et al.* (1986) and Amann *et al.* (1987) have evaluated the costs of several receptor-oriented policies in Europe. In some situations, it is possible to achieve low deposition levels at environmentally sensitive receptors at a fraction of the cost of flat-rate reductions. These initial studies indicate that targetted strategies may be advantageous, and further investigation seems warranted.

2.2. Limitations of targetted strategies

The usefulness and acceptance of targetted strategies may be impeded by a number of factors. First, acidification is a multifacetted problem. Targetted strategies must be multiobjective, and thus solutions will be subjective and depend on the decision-maker. The mathematical formulation of the decision problem as an optimization problem might be highly simplified, considering only one or two subobjectives, for example. In addition, models usually have a strong bias towards expected or average results. Poor or even catastrophic outcomes, to which decision makers may be especially averse, may not be modeled due to their presumed low probability.

A second factor impeding the acceptance of targetted strategies is the high degree of political cooperation required for implementation. Environmental impacts often occur hundreds of kilometers from pollutant sources and perhaps in a different country, and thus cause-effect relationships may appear tenuous. Cost sharing or cost shifting mechanisms may be useful to equalize the costs and increase the benefits of controlling transboundary pollutants.

A third factor concerns the mathematical models used to formulate and evaluate strategies. These models have various errors, both known and unknown. If the errors are large, it may not be possible to design targetted abatement strategies. It is difficult to reliably quantify source-receptor relationships which indicate the contributions of different pollutant sources. While atmospheric dispersion models may produce reasonably accurate long-term (e.g., annual average) predictions, these predictions are the sum of contributions from many countries, and model biases regarding contributions from one country may be compensated by biases in the opposite direction from other countries. In targetted strategies, however, greater demands are placed on the accuracy of individual source-receptor relationships; errors concerning costs, depositions and the overall control strategy may be compounded if source-receptor relationships are inaccurate. Similar conclusions may hold for cost and emission models.

Because of model uncertainty, decision-makers may tend to disregard model results. This possibility may occur whether the models are used in an optimization framework, or in the more conventional "scenario analysis" mode.

A fourth factor is related to environmental targets. Targets may be related to any of the diverse impacts caused by acidic deposition. Targets may use either *direct* indicators of environmental impacts, e.g., forest impacts or lake acidity, or *indirect* indicators, e.g., sulfur concentration and deposition levels. It is extremely difficult to define indirect indicators which will protect forests and lakes, for instance, from damage due to acidification. There are large gaps in the knowledge concerning the environmental consequences of transboundary pollutants, and much of the data necessary to use these models on a large scale is unavailable. Additional difficulties are caused by dynamic ecosystem changes, limitations of current knowledge, and unanticipated developments in both precursor emissions (e.g., from changed energy use patterns) and world climate.

One approach for specifying environmental targets uses critical loadings for sulfur deposition (Nilsson, 1986). These critical loadings represent maximum deposition levels below which no significant environmental impacts are believed to occur in the ecosystem. Such loadings may vary according to the sensitivity of the terrestrial and aquatic environments.

A fifth factor related to targetted schemes, and the one addressed in this paper, relates to the complexity of targetted schemes. In the mathematical specification of the optimization problem, environmental targets form constraints at some or all locations or "receptors" in the modeled domain. For transboundary air pollutants, the modeled domain is often very large, covering Europe or northern North America, for instance. Few areas can be excluded as having no significant environmental impacts from acidic deposition. Thus, the number of environmental constraints may be very large and involve hundreds of sources and receptor locations. The corresponding optimization problem is complex numerically and computationally.

A complete discussion of the limitations of targetted strategies is beyond the scope of this work. Here, targetted strategies are viewed as alternatives to "flat rate" reduction schemes which may merit further discussion and analysis. As the analysis of targetted strategies requires models which integrate many aspects of the problem, this approach perhaps has the greatest usefulness in a pedagogical sense: the models used represent the current state of knowledge and can help focus discussion on the most critical aspects of the problem. Of course, decision-makers and model users should be aware of the assumptions and uncertainties of the models. The model developers should provide a frank assessment of the strengths and weaknesses of their model.

2.3. Influential receptors

Both targetted emission control strategies and more conventional scenario analysis mode of most integrated models share the need to evaluate environmental impacts over a large domain. This is done by calculating ambient concentrations and depositions of sulfur at hundreds of locations, called receptors. Environmental impacts then may be estimated at these locations using ecological models.

The primary task addressed here is the identification of the receptors which influence targetted emission control strategies. Such receptors are called "influential" receptors. If environmental targets are achieved at the influential receptors, they also will be satisfied at all receptors. All other so-called "inactive" receptors may be omitted in the formulation and solution of targetted control policies. The influence of targetted strategies to only a few receptors and source regions has been noted by several researchers, e.g., Ellis *et al.* (1985). In general, just a few receptors and "driving airsheds" were found to limit the available abatement options.

In this paper, several "filters" are developed to identify influential receptors. The filters can be used to select a subset of receptors which are representative and which provide "early warning" of adverse effects. These receptors may be used in both modeling and field studies (to help verify models).

The principal motivation for the present work is the use of these filters in targetted emission control strategies. Environmental targets at influential receptors will form the critical or binding constraints which affect solutions to the optimization problem. Other receptors can be ignored, at least for the purpose of optimizing. Influential receptors are identified before any optimization of emissions, costs or environmental benefits. The filters greatly reduce the number of deposition constraints in optimization problems. For example, the European scale RAINS model contains about 600 land-based receptors (Alcamo *et al.*, 1987). In most optimization problems, however, there are only several dozen influential receptors. This smaller problem is solved much faster. Microcomputer implementations, which have strict limits on the number of constraints, thus become practicable.

2.4. Examples of influential receptors

The interpretation of influential receptors depends on the formulation of the optimization problem. Three examples shown below use the same the objective function, namely, the minimization of total costs, however the environmental targets vary.

1. With maximum deposition limits, e.g., $1\,g/m^2$-year, influential receptors are locations which may experience the peak deposition under some set of emissions.

2. With limits on ecological impacts, e.g., forest damage as indicated by needle loss, influential receptors are locations which may experience the most severe ecological impacts under some emission condition.

3. With deposition limits based on a specified pattern, e.g., that achieved by a 50% cut in 1980 emissions, the deposition at influential receptors may be closest or equal to the specified limits under some emission conditions.

A different set of influential receptors may be generated for each combination of environmental goals and emission constraints. For example, southern Scandinavia may contain many of the influential receptors for lake acidification, while central Europe may contain the influential receptors for forest damage. Different sets of influential receptors may occur with different pollutants as well. If desired, the separate lists of influential receptors resulting from each indicator may be combined, and one further level of filtering can be used to identify a super-set of influential receptors which includes several indicators.

3. RECEPTOR FILTERS

This section presents three filters which help to identify influential receptors, defined as locations at which concentration, deposition or environmental targets become binding constraints in targetted emission control strategies. The three filters are used respectively to (1) identify receptors which can never exceed environmental targets; (2) identify influential receptors; and (3) test the feasibility of the environmental targets. The approach applies in a general way to optimization problems which have few binding or active constraints in comparison to the number of slack constraints. Before describing the filters, the mathematical definition of influential receptors is given. The chapter also includes a simple example showing pair-wise comparisons used to identify influential receptors. The filters are then extended to handle spatially varying receptor sensitivity and policy constraints.

3.1. Mathematical definition of influential receptors

For simplicity, the following discussion uses sulfur deposition as the environmental indicator. In this case, influential receptors are locations which may produce local maxima in deposition for some set of emissions. The restrictions in the example are relaxed later when the vulnerability or sensitivity of receptors, the cumulative effects of pollution, and policy constraints are incorporated.

First, define feasible emissions S_i as emissions for country or region i between specified upper and lower bounds:

$$S_{i,min} \leq S_i \leq S_{i,max} \qquad (1)$$

These bounds should reflect the expected range of emissions, e.g., from totally unabated to completely controlled. In the European context, vector $\mathbf{S_f}$ contains emissions S_i from 27 European countries, all satisfying the bounds given in Equation (1).

$$\mathbf{S_f} = \begin{vmatrix} S_1 \\ S_2 \\ \vdots \\ \vdots \\ S_{27} \end{vmatrix} \qquad (2)$$

Any vector $\mathbf{S_f}$ that satisfies the constraints in Equation (1) belongs to the feasible emission space, called S, such that $\mathbf{S_f} \in \mathbf{S}$.

Receptors are geographical locations at which pollutant concentrations and depositions are computed. The deposition at receptor k, D_k, is calculated assuming additive effects from each pollutant source region:

$$D_k = \Sigma_i T_{ik} S_i + B_k \tag{3}$$

where T_{ik} represents the dispersion, chemical transformation and deposition of sulfur emissions from country i to receptor k, and B_k is "background" or deposition at receptor k which is uncontrollable or unattributed to specific emission sources. Using matrix notation, depositions are calculated at all receptors in vector **D** using the vectors of emissions **S** and background levels **B** and the transport matrix **T**:

$$\mathbf{D} = \mathbf{T}\,\mathbf{S} + \mathbf{B} \tag{4}$$

(Individual receptors correspond to rows of the transport matrix.)

Receptor j is an influential receptor if the highest deposition among all receptors occurs at the jth location for *some* feasible vector of emissions $\mathbf{S_f}$ satisfying Equation (1):

$$(D_j \mid \mathbf{S_f}) > (D_k \mid \mathbf{S_f}) \text{ for some } \mathbf{S_f} \in \mathbf{S};\ \text{ for all } j \neq k \tag{5}$$

Influential receptors may be viewed as locations of local maximum for all possible samples of emissions in the feasible emission space. (This problem is different from simply determining the *single* site at which the maximum deposition occurs, which is the receptor with the highest deposition when all emissions are at the upper bounds.) In general, there may be several or many influential receptors, depending on the transport matrix **T** and the feasible emission space. These receptors may be identified using the filters described below.

3.2. Filter 1: Identifying receptors which cannot exceed targets

The first and extremely simple filter identifies and eliminates receptors at which the deposition calculated using the maximum feasible emissions, e.g., the unabated situation, is below a specified target, $D_{tar,k}$:

$$\text{if } (\Sigma_i T_{ik} S_{i,max} + B_k) \le D_{tar,k} \text{ then eliminate receptor k} \tag{6}$$

Eliminating receptors using Equation (6) does not establish whether the remaining receptors are influential. It helps to reduce the computational work required in the next step, however.

3.3. Filter 2: Identifying influential receptors

The second filter identifies influential receptors and may be used after the application of Equation (6). The logic is as follows. Receptors fall into one of two classes, i.e., influential and "inactive" (uninfluential) receptors. Pair-wise comparisons are used to identify some or all of the inactive receptors. By exclusion, the remaining receptors constitute influential receptors.

Substituting Equation (3) into Equation (5), receptor k is inactive if:

$$(T_j\, S_r + B_j) \geq (T_k\, S_r + B_k) \text{ for some } j \neq k; \text{ for all } S_r \in S \qquad (7)$$

Thus receptor k is inactive if its deposition is always smaller than or equal to deposition at some other receptor j. Collecting terms, receptor k is inactive if:

$$(T_j - T_k)\, S_r + B_j - B_k \geq 0 \text{ for some } j \neq k; \text{ for all } S_r \in S \qquad (8)$$

The inactivity of receptor k may be established by finding the smallest difference between deposition at receptors k and j, called d_{jk}:

$$d_{jk} = \min_{S}\, [(T_j - T_k)\, S_r + B_j - B_k] \qquad (9)$$

$$= \min_{S}\, [(\Sigma_i\, (T_{ij} - T_{ik})\, S_i + B_j - B_k]$$

If the "worst case" difference is still positive, then receptor k is an inactive receptor. The minimum is found by observing that extrema in this linear problem occur at edges or corners of the hypercube formed by the feasible emission space. Equation (9) may be evaluated by selecting each S_i such that:

$$S_i = \begin{cases} S_{i,min} & \text{if } T_{ij} > T_{ik} \\ S_{i,max} & \text{if } T_{ij} < T_{ik} \end{cases} \qquad (10)$$

S_i is indeterminate and irrelevant if $T_{ij} = T_{ik}$. It should be noted that d_{jk} has no relationship to d_{kj}. Both values must be computed.

The process described above identifies a *subset* of the inactive receptors since Equation (9) eliminates receptors which are inactive with respect to only *single* receptors. It does not eliminate receptors which are inactive as established by two or more receptors. For example, receptor m may have greater deposition than receptor k in one portion of the feasible emission space; receptor n also may have greater deposition than receptor k in the remaining emission space. Receptor k would not be eliminated using Equation (7) although its deposition is always less than or equal to depositions at one of the other receptors. As defined by Equation (5), receptor k is inactive as it never produces the maximum deposition. This situation is analogous to elements of a correlation matrix: each element indicates a single dependency between pairs of variables, but not the dependencies involving three or more variables, i.e., multiple colinearity. However, even the subset provides a great reduction in the number of receptors considered.

Tolerance

An optional step may be used to further reduce the number of receptors included in the influential set. For practical purposes, influential receptors which obtain just slightly higher depositions than other receptors may be eliminated. A tolerance level, D_{tol}, may be specified to define the cutoff point. The tolerance may be specified as a fraction (e.g., 1%) of the maximum deposition.

With a tolerance, receptor k is inactive if:

$$(T_j - T_k)\, S_f + B_j - B_k + D_{tol} = 0 \quad \text{for some } j \neq k; \text{ for all } S_f \in S \tag{11}$$

To use a tolerance, Equation (11) replaces Equation (8); D_{tol} is also added to the right hand side of Equation (9). This step destroys some properties (including uniqueness) of the set of influential receptors. However, the remaining subset of influential receptors may be much smaller and entirely satisfactory.

To implement filter 2, pair-wise comparisons between all receptors are required. With several hundred or thousands of receptors, this is a large number of comparisons. However, once a receptor is determined as inactive, it may be eliminated from further consideration. A solution strategy was designed to exploit this fact and speed computation. Initially, a receptor is selected which is expected to be influential, e.g., one with a high deposition. This receptor is compared to all other receptors, many of which are likely to be inactive and thus eliminated. In subsequent iterations, receptors are selected in the same manner. This procedure was found to be extremely efficient with respect to maximum deposition.

3.4. Filter 3: Identifying the feasibility of target loadings

The final filter is used simply to determine if the target can be attained in the feasible emission space. If the target can be achieved at minimum emissions, that is:

$$\Sigma_i T_{ik} S_{i,min} + B_k \leq D_{tar,k} \tag{12}$$

can be satisfied for each receptor, the optimization problem is feasible and a solution exists. If this equation cannot be satisfied at some receptors, then no solution can be obtained, and the targets and/or the minimum emission vector must be modified. This filter is used only to avoid the time consuming optimization process for a problem which has no feasible solution.

3.5. Example problem

A simple example using 4 receptors (A,B,C,D) and 2 emitters (1,2) is used to demonstrate the pair-wise comparisons described in the previous section. The range of feasible emissions and transport matrix are given below. For simplicity, no background concentrations are assumed.

Emission ranges: $4 \leq S_1 \leq 10$ $\quad$ $2 \leq S_2 \leq 5$

Transport matrix:

receptor	country 1	country 2
A	15	30
B	10	25
C	40	10
D	5	30

First, receptors A and B are examined. Equations (10) and (11) are used to compute the minimum difference between these receptors, d_{AB}:

$$d_{AB} = \min_{S_I}[(T_A - T_B)\ S_I]$$

$$d_{AB} = (15-10)\ 4 + (30-25)\ 2 = 20$$

Since $d_{AB}>0$, receptor B is an inactive receptor. Of course, this may be determined by inspection in this example since receptor B has smaller coefficients for both countries than receptor A, and thus always has a lower concentration. Next, receptors A and C are compared:

$$d_{AC} = (15-40)\ 10 + (30-10)\ 5 = -150$$

Receptor C cannot be eliminated as $d_{AC} \le 0$. Comparing receptors A and D:

$$d_{AD} = (15-5)\ 4 + (30-30)\ S_2 = 40$$

Since $d_{AD}>0$, receptor D may be eliminated. As only two receptor remain, we only need to compute d_{CA}:

$$d_{CA} = (40-15)\ 4 + (10-30)\ 5 = 0$$

Receptor A can be eliminated since $d_{AC} \le 0$. Thus, of the four receptors, only receptor C is influential. It is sufficient to use only this receptor in optimizations with the objective of reducing the maximum deposition at the four receptors.

3.6. Spatially varying receptor sensitivity

Different soil types, hydrological domains, flora and fauna may have different responses to the same level of pollutant deposition or ambient concentration. Thus, the sensitivity or vulnerability to pollution varies spatially over the receptors. If the relative sensitivity or environmental impact can be expressed as a linear function of deposition or concentration, the filter described in Section 3.3 may be used to identify influential receptors. The linearity requirement may not be too restrictive as threshold effects are satisfactorily represented, and linearization may be adequate for many purposes. Further flexibility is gained by the specification of only *relative*, not absolute, response functions. For example, it is adequate to specify that an area is 50% more sensitive than another, or has a threshold effect 2 g/m^2-yr lower.

The sensitivity of receptor j is defined to be *linear* if the environmental indicator or response, given by function R, is a linear and/or threshold function of deposition or concentration D_j:

$$R_j(D_j) = \delta(D_j - k_{0j})(k_{1j} + k_{2j} D_j) \tag{13}$$

where $\delta(D_j - k_{0j})$ is zero if concentration D_j is lower than threshold k_{0j} and unity otherwise; k_{1j} and k_{2j} are the intercepts and slope of the indicator function. These three parameters are site-specific. While Equation (13) implies strictly linear dose-response functions, in the context of finding influential receptors, it is a fairly flexible formulation. Equation (13) may represent (1) "proportionally" varying sensitivity, (2) threshold effects, and (3) cumulative dosages or past environmental "strain," as shown below.

Proportional effects are modeled by k_{2j}. For example, a doubling of k_{2j} (with k_{1j}=0) represents an area which is "twice as sensitive" to the same amount of deposition.

Some models of environmental response use concentration or deposition thresholds, below which no adverse effects are assumed to occur. In this case, k_{1j} is set to the negative of the threshold concentration.

Cumulative or historical effects of pollutant exposure may be modeled using Equation (13) by calculating the "environmental strain" at receptor j, f_j, as

$$f_j = R_j(D_{j,t1} \cdots D_{j,t2}) \tag{14}$$

where the response is a function of deposition from time t_1 to time t_2. The strain is added to the intercept term k_{1j}. Note that the long term (historical) response function is not limited to linear forms (the short term dose-response relationship still must be linear.) The historical strain may be calculated as an ***current equivalent deposition*** D_{*j}:

$$D_{*j} = R_j^{-1}(f_j) \tag{15}$$

This technique is exact if a linear response model (where impact is a function of cumulative total dosage (where dosage = pollutant level x exposure time) is used.

Spatially varying functions may be incorporated into the formulation by modifying the threshold concentration D_{thres}, the vector of background concentrations $\mathbf{B}$, and transport matrix $\mathbf{T}$ to D_{*thres}, B_{*j} and T_{*ij}, respectively, for all receptors:

$$D_{*thres} = k_{0j} \tag{16a}$$

$$B_{*j} = B_j + D_{*j} - \min(k_{0j}, k_{1j}) \tag{16b}$$

$$T_{*ij} = T_{ij} k_{2j} \tag{16c}$$

3.7. Policy constraints

As mentioned earlier, it is difficult and controversial to define deposition or concentration objectives on the basis of environmental impacts. As an alternative to such *receptor-based* goals, deposition constraints may be formulated on the basis of emission goals in a *source-based* strategy. As an example, a number of countries have agreed to reduce emissions from 1980 levels by at least 30% by 1993. The deposition pattern resulting from these emission reductions, or some other emission pattern, might serve as constraints in targetted emission reduction strategies to minimize aggregate European costs. In the case of 30% uniform reductions for all emitters, the deposition at each receptor, D_j, must satisfy the following constraint:

$$D_j \leq G_j \tag{17}$$
$$G_j = 0.7\ \Sigma_i\ T_{ij}\ S_{i,1980} + B_j$$

where $S_{i,1980}$ is the 1980 emissions from country i. Receptor k will be inactive if its deposition constraint is satisfied ***whenever*** the deposition constraint on some other receptor, say receptor j, is satisfied for all feasible emission vectors $\mathbf{S_f}$:

$$(D_k|\mathbf{S_f}) \leq G_k \text{ if } (D_j|\mathbf{S_f}) \leq G_j \quad \text{for all } \mathbf{S_f}\ \varepsilon\ \mathbf{S}; \text{ for some } j \neq k \tag{18}$$

Equation (18) may be written as:

$$(G_k - D_k|\mathbf{S_f}) \geq 0 \quad \text{if } (G_j - D_j|\mathbf{S_f}) \geq 0 \text{ for all } \mathbf{S_f}\ \varepsilon\ \mathbf{S}; \text{ for some } j \neq k \tag{19}$$

There is a subtle difference between Equations (19) and (5) used to define an influential receptor in the case of meeting a single deposition limit. Unlike Equation (5), Equation (19) permits no comparison between levels at receptors j and k. However, receptors are always inactive if they have equal or greater "slack" or margin in meeting deposition goals than other receptors. Thus, inactive receptor k would meet deposition targets by an amount equal to or larger than those at influential receptor j:

$$(G_k - D_k|\mathbf{S_f}) \geq (G_j - D_j|\mathbf{S_f}) \geq 0 \text{ for all } \mathbf{S_f}\ \varepsilon\ \mathbf{S}; \text{ for some } j \neq k \tag{20}$$

This is more restrictive than by Equation (19), i.e., fewer receptors would satisfy Equation (20). However, because the transport matrix T contains only positive elements, Equations (19) and (20) produce equivalent results. Thus, Equation (20) may be treated like Equation (9); receptor k is inactive if there exists a receptor j such that

$$(G_k - D_k|\mathbf{S_f}) \geq (G_j - D_j|\mathbf{S_f}) \quad \text{for all } \mathbf{S_f}\ \varepsilon\ \mathbf{S}; \text{ for some } j \neq k \tag{21}$$

Multiplying through by negative one, we obtain a form similar to Equation (9):

$$(D_k|\mathbf{S_f} - G_k) \leq (G_j - D_j|\mathbf{S_f}) \quad \text{for all } \mathbf{S_f}\ \varepsilon\ \mathbf{S}; \text{ for some } j \neq k \tag{22}$$

The procedure given by Equation (16b) is used to account for deposition goals by adjusting the constant or background term:

$$B_{*j} = B_j - G_j \qquad (23)$$

4. EXAMPLES OF INFLUENTIAL RECEPTORS IN EUROPE

This chapter presents several examples of influential receptors in Europe, including:

- Reducing the highest sulfur deposition in Europe;
- Reducing the highest rural SO_2 concentrations in Europe; and
- Maintaining the deposition pattern resulting from a 50% reduction in 1980 SO_2 emissions.

Because of data and modeling limitations, information concerning receptor sensitivity – that is, direct environmental indicators – was not used. Only indirect indicators, SO_2 and sulfur deposition are used. Thus, the influential receptors in these examples may not correspond to areas which suffer the most severe environmental impacts. However, the examples illustrate the utility of the receptor filters.

The examples use transport coefficients obtained from the EMEP-1 atmospheric transport model. The EMEP model generates SO_2 concentrations and sulfur deposition (both wet and dry) in a grid (of dimension 27 × 31) covering Europe, western Asia, and northern Africa. A somewhat smaller area, laying between 12° W and 42° E, and 35° N and 72.5° N is considered in this paper. The locations of the 650 receptors contained in this area are shown in Figure 1. The transport coefficients are developed by simulating four years of meteorology (fall, 1978 to summer, 1982) is used. (The model is described by Eliassen and Saltbones, 1983; and WMO, 1984.)

Emissions for the three cases are based on historical (1980) emission data. (A description of these emissions may be found in Batterman *et al.*, 1986). Emissions from 27 countries are considered. Several sets of emission constraints are used as the actual emission reduction potential is unknown. In addition, the different constraints illustrate the sensitivity of the number and location of influential receptors to the feasible emission space.

4.1. Peak sulfur deposition

Figure 2 shows the locations of the influential receptors for the first case in which the maximum sulfur deposition is reduced. In each figure, the maximum emissions of each country $S_{i,max}$ are the 1980 emissions. The minimum emissions $S_{i,min}$ are 33 and 10% of 1980 emissions in the figures, respectively. These limits apply to each of the 27 countries modeled. Thus, the two figures representatively represent a three and ten-fold range in emissions.

With the three-fold range in emissions, there are only 4 influential receptors. The number of influential receptors increases rapidly as greater variation in is permitted in emissions. In all cases, the number of influential receptors has been greatly reduced from the 650 originally considered.

4.2. Peak SO_2 concentrations

Figure 3 shows locations of the influential receptors with respect to maximum SO_2 concentrations using the same emission ranges as in the previous section. The pattern for SO_2 is similar to results obtained for sulfur deposition, although it is shifted somewhat to the south. Also, there are more influential receptors for SO_2 than for sulfur deposition. These differences result from the different transport matrices: maximum SO_2 levels occur relatively close to emission sources, while significant sulfur deposition requires longer distances. Prevailing northerly winds have greater influence on sulfur deposition. In addition, sulfur deposition patterns tend to be smoother and more diffuse, resulting in fewer "peaks" and thus fewer influential receptors for the problem considered.

4.3. Flat rate deposition reductions

The flat rate or uniform emission reductions currently considered would result in a "flat rate" deposition reduction (neglecting the background term). For example, a 50% flat rate emission reduction would lead to a similar change in sulfur deposition. (Model assumptions concerning linearity, i.e., the invariance of the transport coefficients to emissions, cannot be discussed here.) In this section, these deposition levels are used as deposition targets.

Figure 4 shows the location of influential receptors for sulfur deposition based on a 50% flat rate reduction in emissions. In this case, a tolerance of $0.1\,g/m^2$-yr was used. For this indicator, the filters are much less effective in eliminating receptors.

5. DISCUSSION AND CONCLUSION

This paper has presented an approach to finding the receptors which may influence the outcome of targetted emission strategies. Any constraints that are a linear function of emissions can be handled similarly. The method is quite general and applicable to many optimization problems.

In the examples related to peak concentrations or depositions, there are relatively few influential receptors. This arises due to the similarity (colinearity) of transport coefficients for nearby receptors, and the relatively few very strong "peaks". Only about half the receptors in the flat rate reduction case were omitted. Most likely, many additional receptors would be eliminated if the filter was able to determine dominance with respect to two or more receptors simultaneously.

Only influential receptors need be modeled to determine optimization results and/or worst-case environmental impacts using a scenario-analysis model. Thus, identifying influential receptors simplifies the generation and evaluation of emission abatement strategies. As relatively few receptors remain after application of the filters, microcomputer based implementations of optimization and scenario analysis models become far more practical.

Currently, simple linear optimization models have been used to generate optimal emission strategies. Modeling of nonlinear environmental indicators, however, will require more effort. In this case, the identification of influential receptors will be most beneficial.

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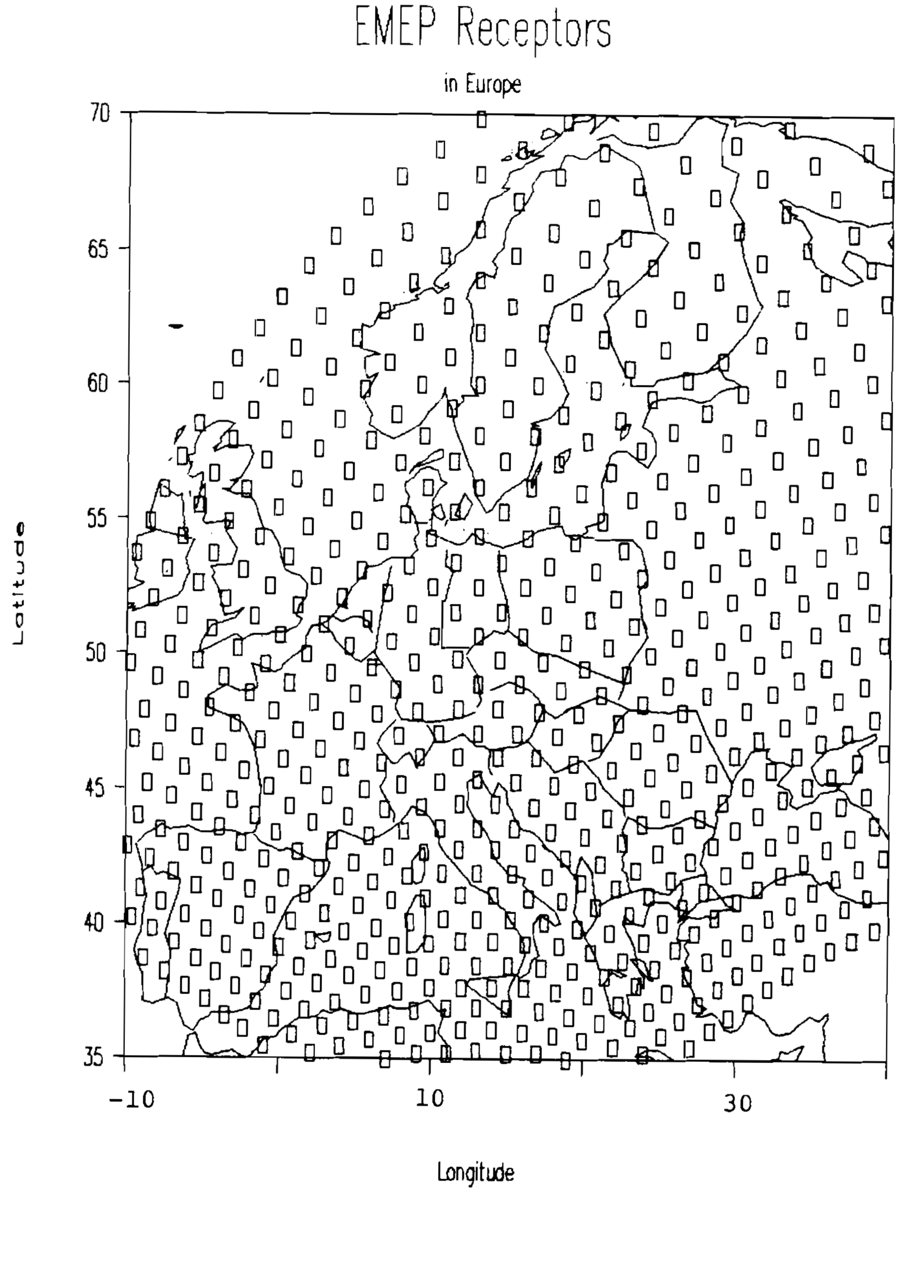

Figure 1. Locations of EMEP receptors. Squares indicate receptor locations.

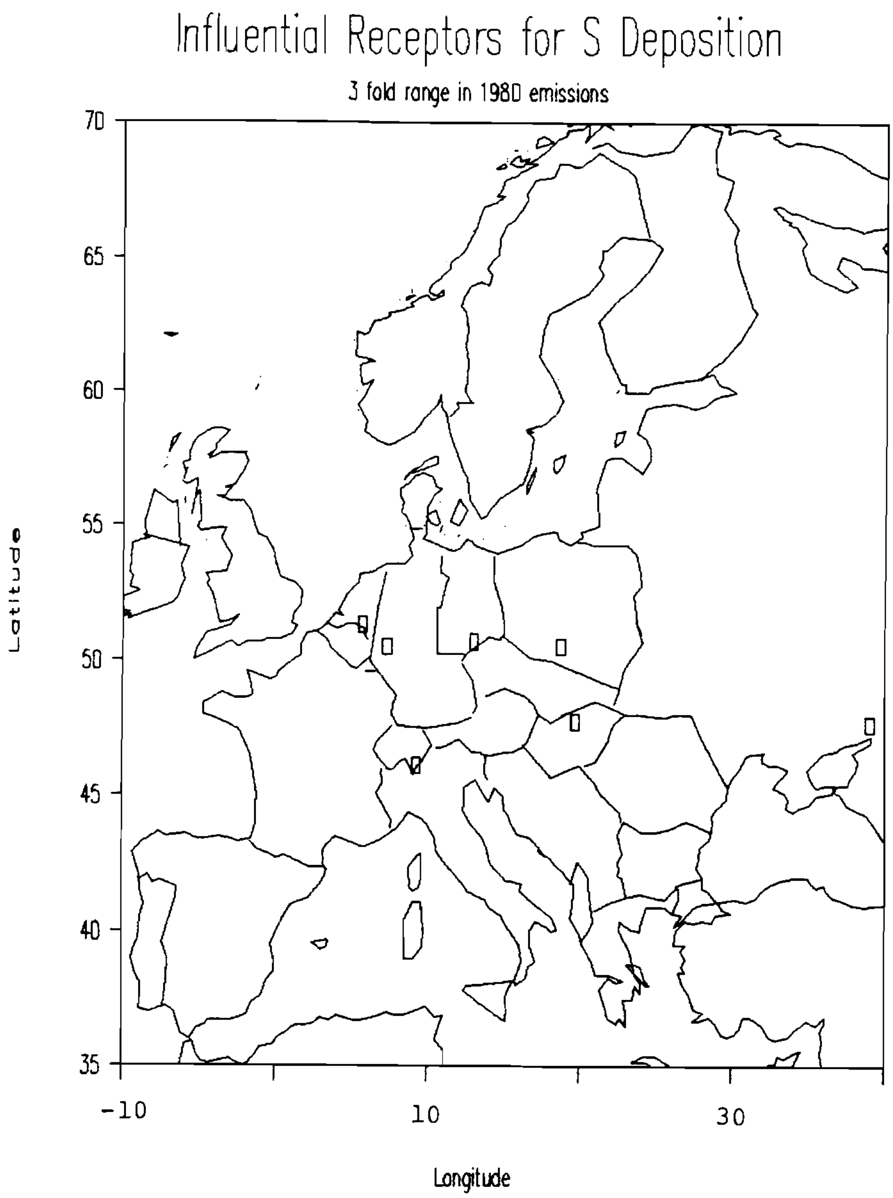

Figure 2a. Locations of influential receptors for sulfur deposition for 3-fold range of feasible emissions. Squares indicate receptor locations.

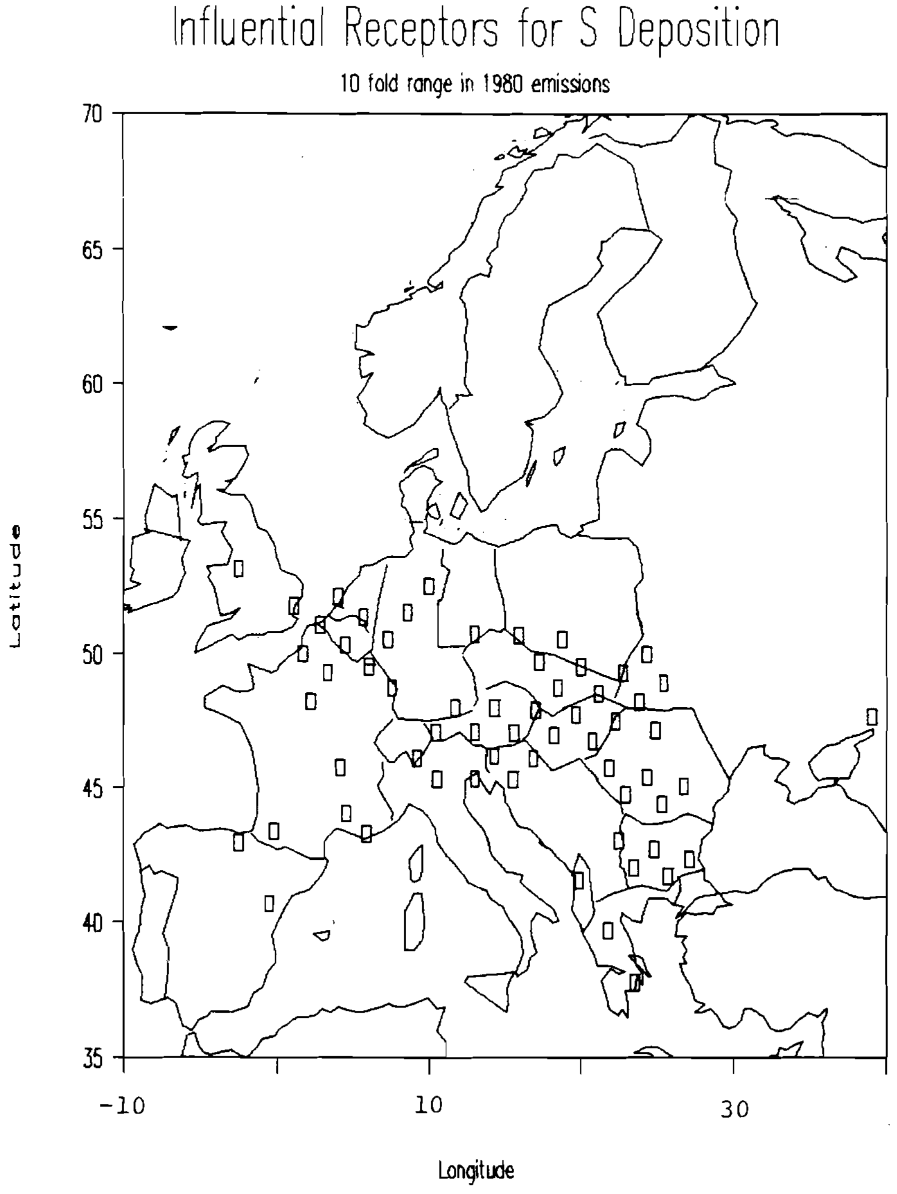

Figure 2b. Locations of influential receptors for sulfur deposition for 10-fold range of feasible emissions. Squares indicate receptor locations.

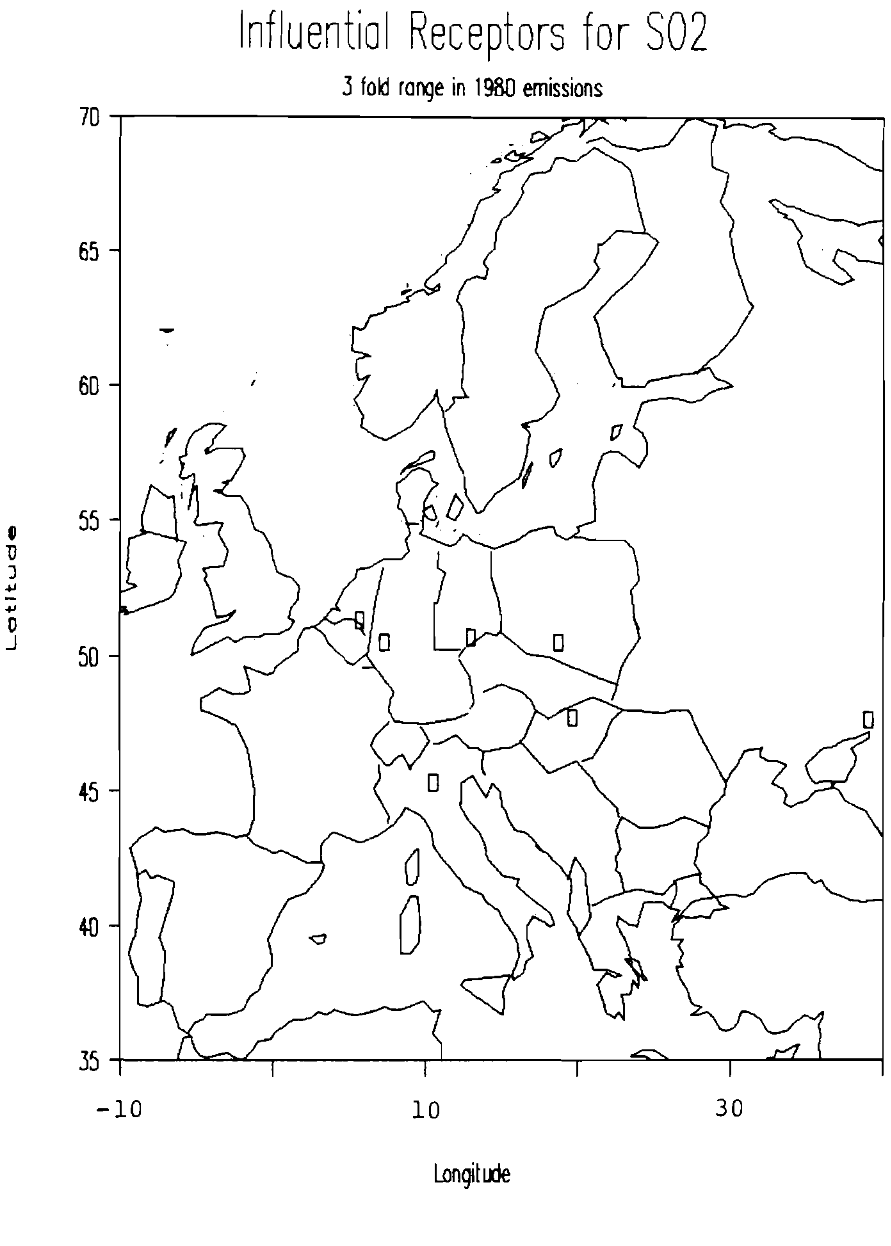

Figure 3a. Locations of influential receptors for SO_2 concentrations for 3-fold range of feasible emissions. Squares indicate receptor locations.

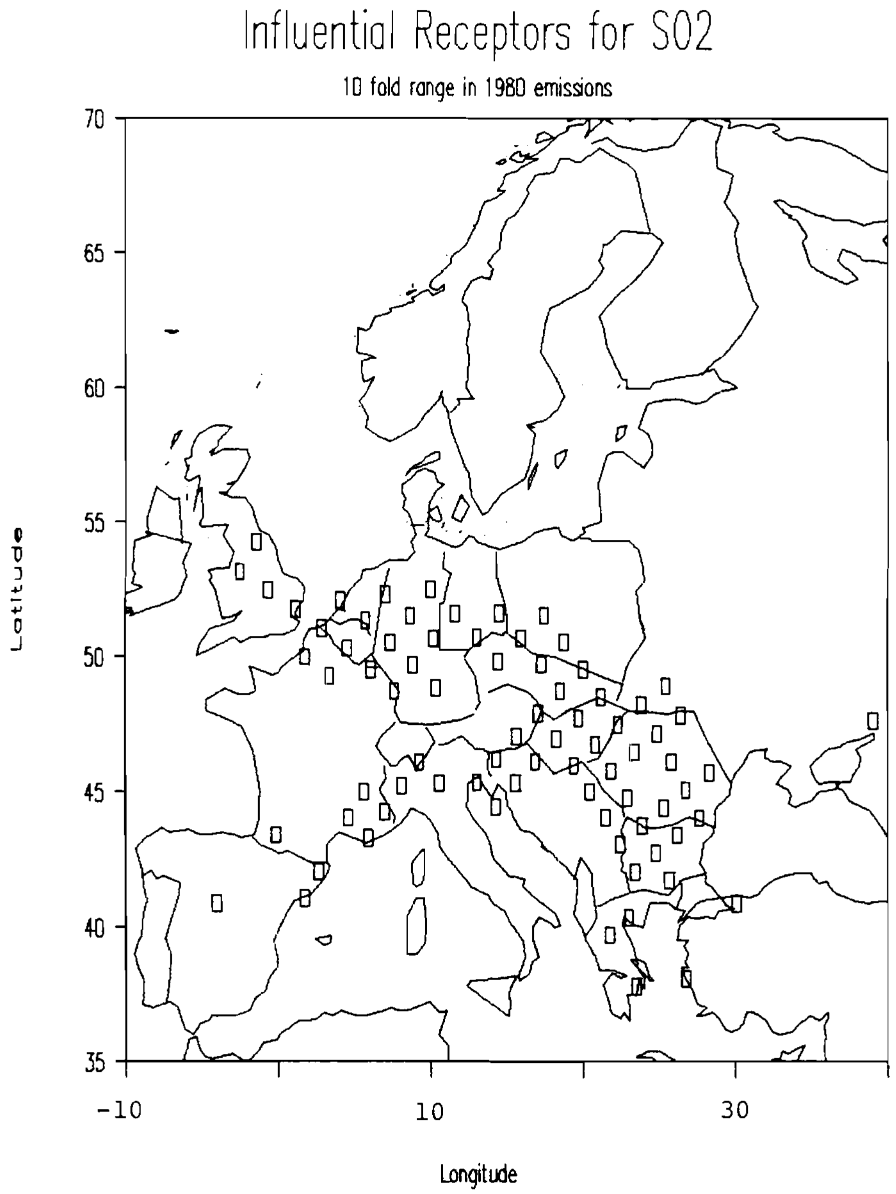

Figure 3b. Locations of influential receptors for SO_2 concentrations for 10-fold range of feasible emissions. Squares indicate receptor locations.

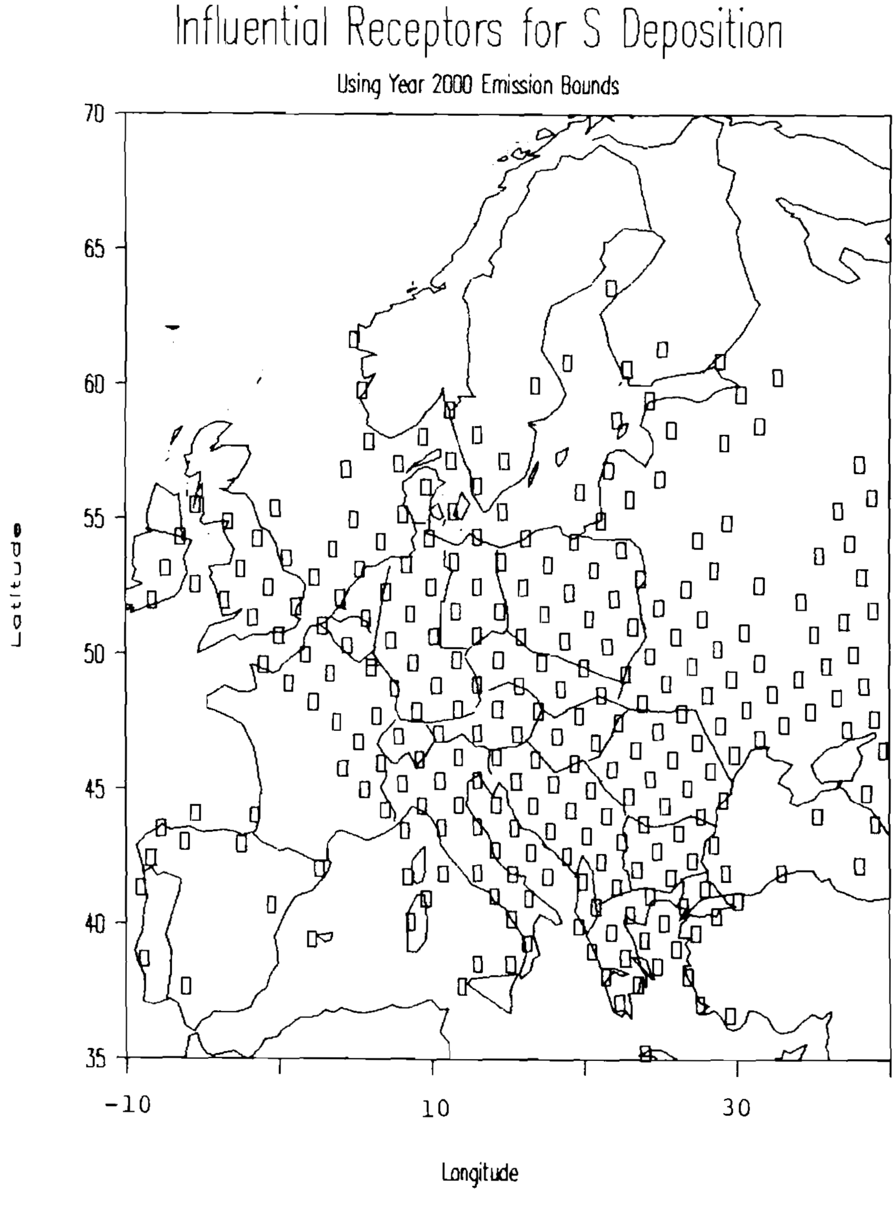

Figure 4. Locations of influential receptors to achieve a 50% reduction in 1980 deposition. Squares indicate receptor locations.