Working Paper

ACID RAIN IN EUROPE : A FRAMEWORK TO ASSIST DECISION MAKING

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Maximillian Posch
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April 1984
WP-84-32

International Institute for Applied Systems Analysis
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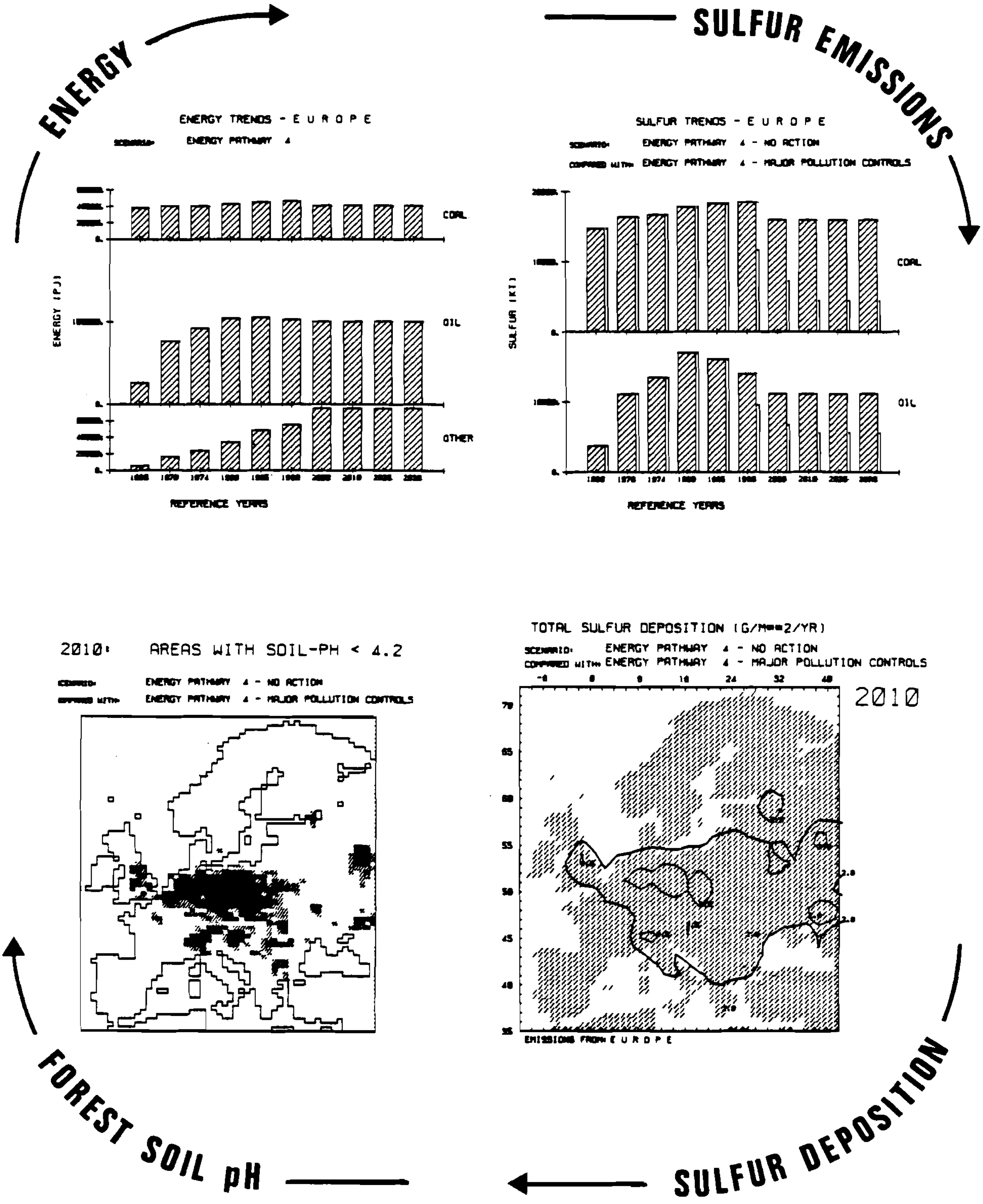

Frontispiece. A sample scenario from the IIASA acid rain model.

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PREFACE

IIASA's Acid Rain Project is a response to the need of the international community for a technical overview of the acid rain problem in Europe. Part of our effort is devoted to reconciling diverse scientific views on the issue by providing a meeting place for scientists from different countries and disciplines. We also wish to help identify critical gaps in understanding the processes of acid rain, and more broadly, transboundary air pollution. Our principal goal, however, is to assist decision makers in evaluating the most effective strategies for controlling acid rain impacts in Europe. This paper describes the progress towards this goal accomplished at IIASA during 1983. The effort was led by Eliodoro Runca (Italy). Other Acid Rain Project staff included Joseph Alcamo (USA), Pekka Kauppi (Finland) and Maximillian Posch (Austria). At the end of 1983 Eliodoro Runca returned to Italy and Technital (Verona) and Pekka Kauppi to the Forest Research Institute in Helsinki, Finland. They were replaced by Juha Kämäri (Finland) and myself (from the Netherlands) as the new project leader.

Leen Hordijk
Project Leader
Acid Rain Project

ACKNOWLEDGEMENTS

We would like to acknowledge the contributions of our colleagues at IIASA who helped us conduct the work described in this paper: Juha Kämäri, Lea Kauppi, M. Khondker, Mark Tumeo and Sergei Orlovsky. We thank Vicky Hsiung for her speedy and accurate typing of this manuscript. We also wish to thank Egbert Matzner (University of Göttingen, FRG) and Anton Eliassen (Norwegian Institute of Meteorology, Oslo) for sharing the results of their work with us. In addition, we are indebted to many scientists outside IIASA for providing key advice to our group, especially Göran Ågren (Swedish University of Agricultural Sciences, Uppsala), J. Pruchnicki and Jerzy Bartnicki (Institute for Meteorology and Water Management, Warsaw, Poland), G. Gravenhorst (Laboratoire de Glaciologie, Grenoble, France), Pertti Hari, Anniki Mäkäla and Taisto Raunemaa (University of Helsinki, Finland), Robert Lamb (U.S. Environmental Protection Agency), Göran Nordlund (Institute of Meteorology, Helsinki, Finland), Joop den Tonkelaar (Royal Netherlands Meteorological Institute, deBilt), and Douglas Whelpdale (Environment Canada, Downsview, Ontario).

We wish to thank members of IIASA's Energy Systems Group and Computer Services Department for their special assistance. We have also benefited from discussions about the concept of Adaptive Resource Management with Carl Walters, Michael Staley and their colleagues. Our group is indebted to the Geneva offices of the World Meteorological Organization and the Economic Commission of Europe (EMEP Program) for providing important data for our project.

Many people have shown support for our project at key junctures. For this support we are especially indebted to Göran Persson (Swedish Environmental Protection Board, Solna), Anders Karlqvist (Swedish Council for Planning & Coordination of Research, Stockholm), Hans Georgii (Institute for Meteorology and Geophysics, Frankfurt, FRG), and Erich Weber (Ministry of Interior, Bonn, FRG), as well as IIASA colleagues, C.S. Holling, Janusz Kindler and Chester Cooper. Finally, we wish to thank Leen Hordijk, the new Acid Rain Project Leader for assisting with the publication of this paper.

SUMMARY

The ratification of the Geneva Convention on Transboundary Air Pollution in March of 1983 showed that nations of Eastern and Western Europe were determined to control the problem of acid rain. In the same year, IIASA offered its analytical skills to the international community to help solve the problem. It did so by entering into official cooperation with the UN Economic Commission of Europe (ECE) which is responsible for implementing the convention. As part of this cooperation IIASA is developing a computer model which can be used by decision makers to evaluate policies for controlling the impact of acid rain in Europe. In addition, we hope that our work will help identify gaps in understanding the acid rain problem and stimulate the research necessary to overcome these gaps.

This paper describes the status of the acid rain model after approximately one year's work. It also presents some examples of how the model is used and the type of information it provides.

A POLICY ORIENTED TOOL

Since the model is designed to be especially useful to decision makers, we have tried to ensure that it is both *comprehensible* and *relatively easy to use*. In addition it should incorporate past and current research in the acid rain field, yet deal with the most important issues first. Other desirable characteristics are (1) flexibility in incorporating new information as it becomes available and (2) explicitness in treating uncertainty.

Based on the above criteria, we have established the following model guidelines:

1. The model system should be co-designed by analysts and potential model users.
2. The model should be of modular construction and consist of a series of linked *submodels*.
3. Submodels should be as simple as possible and be based, when feasible, on more detailed models or data. They should be made more complex only if necessary and only in conjunction with potential model users.

4. The model should have interactive input and clear graphical output.
5. The model should present a temporal picture of the problem.

The model, as designed, reflects a systems analytical point of view by providing an overview of different parts of the acid rain problem in Europe. These parts include:

- The energy system of each country in Europe, and how this energy system contributes to acid rain by emitting sulfur dioxide to the atmosphere.
- The atmospheric transport, transformation and deposition of pollutants.
- The environmental impact of acidifying deposition.

As a starting point, the IIASA model currently contains one submodel for each of these parts.

CURRENT SUBMODELS

The first submodel, the *Energy-Emissions* submodel, computes sulfur emissions for each of the 27 European countries based on a selected ***energy pathway*** for each country. The model user has a choice of four possible pathways for each country, each of which is based on published estimates from the Economic Commission of Europe (ECE). Each energy pathway specifies how much energy will be used by four fuel types in a country: oil, coal, gas and ***other***. The sulfur-producing fuels - oil and coal - are broken down further into 12 sectors. Oil has the following sectors: conversion, conventional power plants, low sulfur power plants, industry, domestic, transportation and feedstocks. Coal sectors include: conversion, conventional power plants, low sulfur power plants, industry and domestic. There is an additional sector which accounts for sulfur emissions which do not originate from fossil fuel use, for example, the sulfur emitted by sulfuric acid plants.

The model can compute sulfur emissions for each country with or without pollution control. To reduce sulfur emissions, the user may specify any combination of the following four pollution control alternatives:

(1) flue gas control devices

(2) fuel cleaning

(3) low sulfur power plants, e.g. fluidized bed plants

(4) low sulfur fuel

The sulfur emissions computed for each country are then input into the second submodel, the *Atmospheric Processes* submodel. This submodel computes sulfur deposition in Europe due to the sulfur emissions in each country and then adds the contributions from each country together to compute the total sulfur deposition at any location in Europe. The submodel consists of a source-receptor matrix, which gives the amount of sulfur deposited in a grid square (roughly 100 x 100 kilometers) due to sulfur emissions in each country in Europe. The source-receptor matrix is based on a more complicated model of long range transport of air pollutants in Europe. This model accounts for the effects of wind, precipitation and other meteorologic and chemical variables on sulfur deposition. The source-receptor matrix was made available to IIASA by the Institute of Meteorology in Oslo, Norway.

The sulfur deposition computed by the second submodel is then input to the third submodel the *Forest Soil pH* submodel. We analyze soil pH as an indicator of potential forest and aquatic impact of acidification. The soil pH submodel converts sulfur deposition to acidic deposition, and then compares this deposition with the neutralizing ability of Europe's soils. Based on this comparison, the model computes an average soil pH. This submodel is based on research conducted largely at the University of Göttingen in the Federal Republic of Germany.

As the model currently stands, sulfur pollution is used as an indicator of the acid rain problem since sulfur is recognized as the principal contributor to acid deposition and acidification of the natural environment in Europe. The model will be expanded in the future to include NO_x and possibly other air pollutants.

HOW THE MODEL IS USED

To use the model, the user first selects an energy pathway for each country. Secondly, he/she specifies a pollutant control program. The model then calculates the sulfur emissions for each country, the pollutant deposition resulting from the emissions of each country, and the resultant environmental impact. Model results are displayed in a graphical format. This consistent set of energy pathway, pollutant emissions, pollutant deposition, and environmental impact is called *a scenario* and the type of analysis is sometimes termed *scenario analysis* (See Frontispiece). The time horizon of these scenarios is 50 years, from 1980 to 2030. Their spatial coverage is virtually all of Europe, including the European part of USSR.

Based on this output, the model user may select another energy pathway and control program to evaluate with the model. In this iterative way, the user can quickly analyze the impact of many different policies.

Table S-1. Glossary of Terms

To aid the reader we present the definitions of frequently used terms in this paper. Since these terms are used in many different ways in the literature, the following definitions should be viewed as *working definitions* pertinent only to this paper.

Acid Rain Stress - The input of H^+ to the top layer of forest soil.

Compartment - One of the major parts of the acid rain problem covered by the IIASA Acid Rain Model. There are currently *three* compartments in the model:

- Energy-Emissions
- Atmospheric Processes
- Environmental Impact

Energy Pathway - A temporal picture of energy use in a country based on consistent set of assumptions, for example, *trends continued from the present.*

Impact Indicator - A variable used to investigate the effect of acid rain. In its current state the model has two of these indicators: sulfur deposition and forest soil pH.

Model System - The model together with procedures for using it.

Scenario - A conditional forecast. In this model a consistent set of energy pathway, sulfur emissions, sulfur deposition and forest soil pH.

Scenario Analysis - A procedure for investigating the implications of a policy by exploring scenarios of different actions.

Submodel - A computer model which represents a particular compartment of the acid rain issue. These submodels are then linked together to provide an overview of the problem.

CHAPTER ONE

INTRODUCTION

This paper is an interim report of the activities of IIASA's Acid Rain Project. The principal objective of the project is to assist decision makers in their evaluation of policies for controlling the impacts of acid rain in Europe. To accomplish this we are developing a model and a set of procedures for using it. Together, we term these a *model system*. Our hope is that this model will serve as a *common technical ground* in the negotiation of an international agreement to mitigate or eliminate acid rain impacts in Europe. In addition we hope that our work will help identify gaps in understanding the acid rain problem and stimulate the research necessary to overcome these gaps.

THE PROBLEM OF ACID RAIN

Society has been plagued with air pollution since the Industrial Revolution. Clusters of smoke stacks plus unfavorable meteorologic conditions resulted in *air pollution episodes*, brief periods of elevated sulfur dioxide and particulate matter levels. In the twentieth century, automobile exhaust added carbon monoxide, nitrogen dioxide, photochemical oxidants and other gases and aerosols to the list of noxious air components. Though the type and intensity of air pollution varied from place to place, most problems were both *local* (covering up to a few hundred square kilometers) and *transitory* (peak pollutant levels usually lasted a few hours or less).

In the last twenty years the dimensions of the air pollution problem have changed dramatically. Smokestacks 200 meters or higher, together with increased pollutant emissions, have made a *local* problem into a ***transboundary*** problem. It is now thought that pollutants in Europe and North America may remain airborne for several days and travel over a thousand kilometers before being deposited. Sulfur and nitrogen oxides in particular can have cumulative effects at locations very distant from their sources. Through a web of processes summarized in Figure 1-1, these pollutants may be converted into a flux of acids to the terrestrial and aquatic environment which is broadly, though not too accurately, termed ***acid rain.****

The acidic compounds due to sulfur and nitrogen emissions have both direct and indirect effects. Direct effects refer to the damage caused by these compounds on the surfaces on which they are deposited. These include corrosion of materials, deterioration of monuments, and damage to foliage. Indirect effects occur after deposition and adversely affect ecosystems of soil, water, and forests. Increased acidity of soil can restrict plant growth, while acidification of groundwater increases the solubility of heavy metals which can in turn affect human and animal health. The acidification of lakes through different mechanisms can limit the diversity and abundance of its aquatic life. Combination of direct and indirect effects is also possible. For example, forest growth can be reduced by both direct deposition of pollutants on the trees and

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*Acid flux from the atmosphere may also come in the form of fog or snow. Also, ***dry*** pollutant gases and particles may add acids to the environment once they dissolve in the moisture of soil or vegetation.

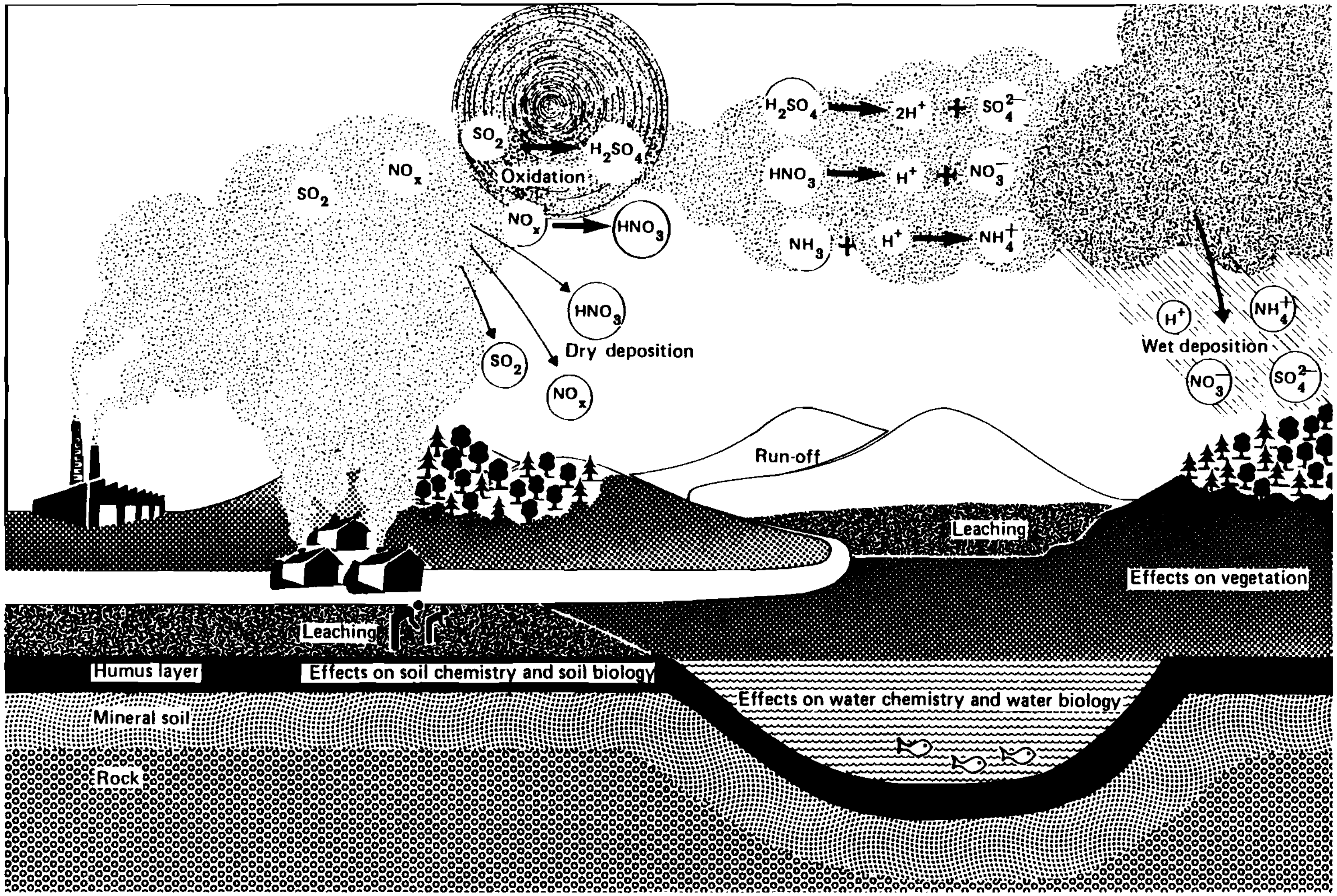

Figure 1-1. Major processes in acidification of the environment. From *Acidification Today and Tomorrow*, Swedish Ministry of Agriculture (1982).

acidification of the soil. Since the rate of soil and water acidification depends on their neutralizing capacity, some areas are more sensitive to acidification than others.

EUROPE'S RESPONSE TO THE ACID RAIN PROBLEM

The control of acidification in Europe is a task of extreme complexity because European countries export different amounts of acidifying compounds to each other and also vary in their sensitivity to acidification. To this must be added that the attitude of a particular country towards environmental issues very much depends on their internal socioeconomic situation.

Wide attention to the transboundary nature of acidification was raised by a Swedish report on the subject presented at the 1972 United Nation Conference for Human Environment in Stockholm. This report marked the official beginning of international programmes on this issue. In 1973, The Organization for Economic Cooperation and Development (OECD) began monitoring and modeling the long-range transport of air pollutants in Europe. This LRTAP project (Long Range Transport of Air Pollutants) was completed in 1977. The project led to the development of a model which estimated the sulfur import-export balance of the European OECD countries, and established the basis for an analysis of cost and benefits of sulfur control. The OECD published results of its analysis in 1980 and 1981.

Monitoring and evaluation of long-range transport of air pollutants continued after 1977 under the cooperative EMEP programme (the Cooperative Programme for Monitoring and Evaluation of Long-Range

Transmission of Pollutants in Europe) which is overseen by the United Nations Economic Commission for Europe (ECE) in collaboration with the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). This new program included both Eastern and Western European countries for the first time. In the same year, Norway proposed the adoption of an International Convention on Transboundary Pollution. The convention was signed by thirty-three countries in 1979, and finally ratified by the required forum of twenty-four countries in January 1983.

The Convention contains no binding commitments to reduce pollutant emissions, but its basic statement says that the countries "shall endeavour to limit and, as far as possible, gradually reduce and prevent air pollution, including long-range transboundary air pollution". The Convention also states that the countries shall, by means of information, consultation, research and monitoring, develop policies and strategies to combat air pollution. To achieve these objectives the convention calls for the following four programs: (a) Air Quality Management, (b) Research and Development, (c) Exchange of Information, and (d) EMEP.

IIASA'S ACID RAIN PROJECT

By ratifying the Convention the signatory countries recognized the need for action to combat "acid rain". In a sense the convention is the result of a cost-benefit study at the political level. However, as noted before, the participating countries have different views on the severity of the problem as well as what to do about it. We felt, in this context, that there was need for a ***framework for the analysis of acid rain control*** *scenarios in Europe*, which could contribute to the programmes defined within the Geneva Convention and at the same time promote research of national institutions on acid rain. In addition, participants in two conferences held in 1982 - the joint IIASA-WHO workshop on air pollution (July 1982) and the Stockholm conference on acidification of the environment (June 1982) - emphasized that this framework should be a joint East-West effort.

IIASA's analytical skills and East-West background made it an appropriate setting for this work. The support, suggestions and recommendations of several members of both the scientific and decision-making community dealing with this issue were of paramount importance in giving shape and consistency to IIASA's initiative. In Winter 1982-83, the objectives of the project and the plan of work were established.

An issue like "acid rain", which involves phenomena very much diversified in space and time, is bound to generate controversial views and understanding. It therefore appears necessary to construct the analytical framework in such a way that it promotes communication between different disciplines and helps reconcile differences in scientific opinion. In other words, the achievement of these objectives depends largely on the way the work is conducted. We chose to operate with a small in-house core group of 4-6 who were closely associated with a large network of collaborating institutions. Through various meetings, the collaborating institutions transfer ideas, data and models to the core group and participate in the design of the model system. The core group is then responsible for constructing the model and translating it into a usable tool for decision makers.

CHAPTER TWO

METHODOLOGY AND MODEL OVERVIEW

It is clear that decision makers will develop policies to control or mitigate acid rain impacts in Europe through a very complicated process. Ultimately these policies will be shaped by a blend of political and scientific, public and private forces. Despite this uncertainty it is also obvious that access to basic *information* can assist decision makers to develop better policies. At a minimum, they need to know the relative effectiveness of different policies in controlling acid rain impacts. This requires the integration of different parts of the problem in a quantitative fashion. To accomplish this quantitative integration we have decided to construct a *computer model*. As mentioned earlier, we term the model plus procedures for using it, a *model system*.

Design of any model system depends very much on (1) the dimensions of the problem it describes, and (2) the users of the model system. Some of the dimensions of the acid rain problem in Europe most relevant to the model system design are:

1. *It is transboundary in nature*. Closely related to this feature is the fact that different countries share different levels of responsibility for acid rain impacts and differ in susceptibility to air pollution deposition.

2. *The problem is poorly understood.* There is great uncertainty in the underlying scientific processes of acid rain. Moreover there are conflicting views of these scientific processes.
3. *Different time scales are important.* The travel time of air pollutants from one country to another may be a few hours to a few days; snowmelt releases acidity to lakes over a few weeks; it may take years or decades for soil to acidify or to implement pollution control policies.
4. *Many different disciplines are needed to understand and solve the problem.* These range from economics and political science to engineering, biology and cloud physics.
5. *New information about the problem is continuously available.* With growing awareness of the problem, more and more funds are being invested in acid rain research. Results of this research sometimes invalidates past understanding of the problem.

Regarding the question of model users, we expect that they will be chiefly *decision makers*. The term *decision maker* is of course open to interpretation but we take it to mean scientific advisors or administrators affiliated with government, some of whom may have a scientific background but all of whom are principally concerned with policy development. We hope also that the model will be used by many others for educational and research purposes.

MODEL SYSTEM GUIDELINES

Combining the dimensions of the problem with assumptions about model users has led us to adopt the following guidelines for our model system.

Since the model is designed for the use of decision makers we believe it should be both *comprehensible* and *easy to use*. In addition it should incorporate past and current research in the acid rain field yet deal with the most important issues first. Other desirable characteristics are (1) flexibility in incorporating new information as it becomes available, and (2) explicitness in treating uncertainty.

Following from the above general criteria, we adopt the following more specific guidelines:

1. *The model system should be co-designed by analysts and potential users.* Though this requires special effort, ultimately it will lead to greater comprehension and relevance of the model system.
2. *The model should be of modular construction.* Each aspect of the problem should be represented by a separate *compartment*. These compartments should then be linked together. Each compartment can be filled by a number of interchangeable *submodels* which permits comparison of different points of view.
3. *Submodels should be as simple as possible yet be based where possible on more detailed data or models.* Model *simplicity* is a relative term but in the context of acid rain, for example, a source-receptor matrix based on a linear relationship between

emissions and deposition is quite simple compared to a model based on non-linear atmospheric chemistry. Advantages of simplicity include: (1) computational time is short, allowing interactive computer use, (2) models are easier to understand, (3) model inputs are simpler which permits simpler and quicker model use. However each simple submodel should be supported where possible by detailed models and data in order to increase the validity of the submodel's estimates. Though submodels should initially be as simple as possible they can also be made more complex if model users and scientific advisors feel that more detail is justified.

4. *To facilitate its use, the model should have interactive inputs and clear graphical outputs.* Communiciation of the model's operation and results should not be an afterthought of model development.

5. *The model should be dynamic in nature.* It is important for decision makers to see how a problem evolves and how it can be corrected over time. Thus it is important for the model to provide a "picture" in time of the causes and effects of acidification.

CURRENT MODEL STATUS

One of the above maxims calls for co-design of the model with its users. Since this process is continuing, the following model description should be viewed as only the *current status* of the model which is subject to revision.

The model currently consists of three linked *compartments*,

- Energy-Emissions
- Atmospheric Processes
- Environmental Impact

Though we imagine that many different *submodels* can be inserted into these compartments, we have begun with three linked submodels illustrated in Figure 2-1.

The first submodel, the *Energy-Emissions* submodel, computes sulfur emissions* for each of 27 European countries based on a selected *energy pathway* for each country. The model user has a choice of four possible pathways for each country, each of which is based on published estimates from the Economic Commission of Europe (ECE). Each energy pathway specifies how much energy will be used by four fuel types in a country: oil, coal, gas and *other*. The sulfur-producing fuels, oil and coal, are broken down further into 12 sectors. Oil has the following sectors: conversion, conventional power plants, low sulfur power plants, industry, domestic, transportation and feedstocks. Coal sectors include: conversion, conventional power plants, low sulfur power plants, industry and

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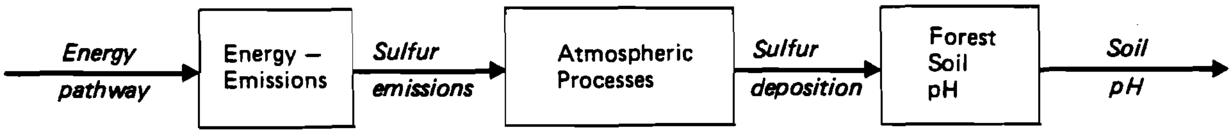
* ***Sulfur emissions*** in this paper refers to a combination of sulfur compounds chiefly sulfur dioxide.



CONTROL ALTERNATIVES
1. Flue gas control
2. Fuel cleaning
3. Low sulfur power plants
4. Low sulfur fuel

Figure 2-1. Current submodels of the IIASA acid rain model.

domestic. There is an additional sector which accounts for sulfur emissions which do not originate from fossil fuel use, for example, the sulfur emitted by sulfuric acid plants.

The model can compute sulfur emissions for each country with or without pollution control. To reduce sulfur emissions the user may specify any combination of the following four pollution control alternatives:

(1) flue gas control devices;

(2) fuel cleaning;

(3) low sulfur power plants, e.g. fluidized bed plants;

(4) low sulfur fuel.

The sulfur emissions computed for each country are then input into the second submodel, the *Atmospheric Processes* submodel. This submodel computes sulfur deposition in Europe due to the sulfur emissions in each country and then adds the contributions from each country together to compute the total sulfur deposition at any location in Europe. The submodel consists of a source-receptor matrix illustrated in Figure 2-2, which gives the amount of sulfur deposited in a grid square (roughly 100 by 100 kilometers) due to sulfur emissions in each country in Europe. The source-receptor matrix is based on a more complicated model of long range transport of air pollutants in Europe developed under OECD and EMEP. This model accounts for the effects of wind, precipitation and other meteorologic and chemical variables on sulfur deposition. The source-receptor matrix was made available to IIASA by the Institute of Meteorology in Oslo, Norway.

The sulfur deposition computed by the second submodel is then input to the third submodel, the *Forest Soil pH* submodel. We analyze soil pH as an indicator of potential forest and aquatic impact of acidification. The soil pH submodel converts sulfur deposition to acidic deposition, and then compares this deposition with the neutralizing ability of Europe's soils. Based on this comparison, the model computes an average soil pH. This submodel is based on research conducted largely at the University of Göttingen in the Federal Republic of Germany.

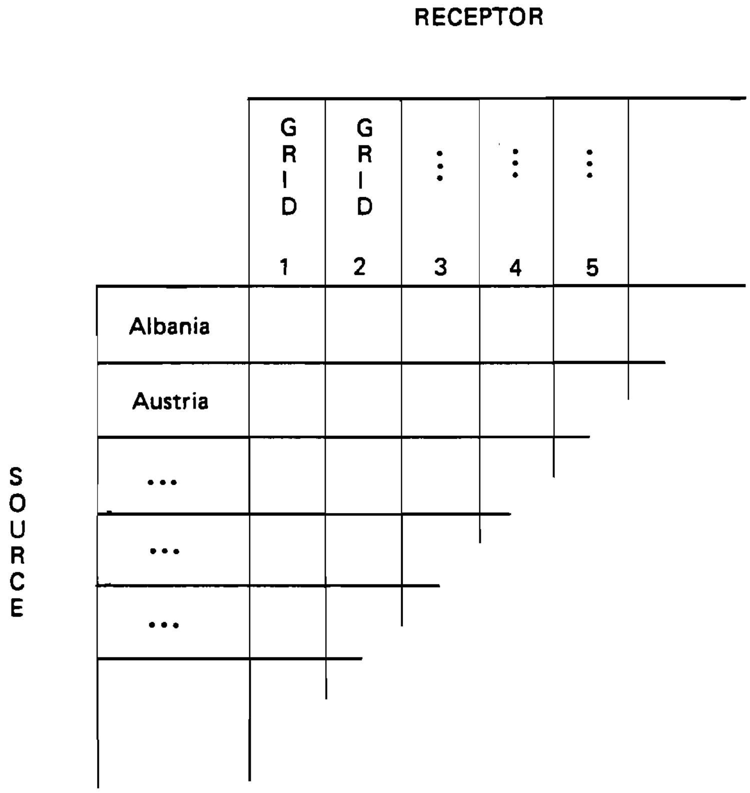


Figure 2-2. Source-receptor matrix of the Atmospheric Processes Submodel.

Table 2-1. Model Features

- Sulfur-based
- 70 year simulation period
  - 20 year past
  - 50 year future
- 3 linked compartments
- Interchangeable submodels
- Dynamic simulation

OTHER MODEL FEATURES

The simulation period begins 20 years in the past so that the model can be tested against historical data where available. The future time horizon is 50 years which permits examination of long-term environmental impacts such as possible soil acidification in forests or groundwater. In addition, 50 years encompasses the turnover time of a country's energy system which permits the possibility of modifying the energy systems of countries to control air pollution.

The model is sulfur-based since it is generally accepted by the scientific community that sulfur is currently the principal contributor to acidification in Europe. In the future, however we expect to include NO_x and other pollutants in our calculations.

The model features are summarized in Table 2-1.

HOW THE MODEL IS USED: SCENARIOS

A decision maker can use the model by the procedure illustrated in Figure 2-3. Typically the model user first selects an *energy pathway* for each country, and then a pollution control program. This information is input to the model which calculates the sulfur emissions of each country, the sulfur deposition throughout Europe resulting from these emissions, and the resultant environmental impact. These calculations are performed for the 50 year time horizon of the model. A consistent set of energy pathway, sulfur emissions, sulfur deposition and environmental impact is called a *scenario* and the type of analysis is sometimes termed *scenario analysis* (see Frontispiece).

Based on this output, the model user may select another energy pathway or control program to evaluate with the model. In this iterative way a decision maker can quickly analyze the impact of many different policies. Details of model use are presented in Chapter 4 and Appendix A. Other ways of using the model apart from scenario analysis are being considered. These are briefly described in Chapter 5.

The flexibility of the model is illustrated by two examples in Figure 2-4. A model user has a choice of both *entry points* and *impact indicators*. *Entry points* refer to the place where the model user begins an analysis. A user may begin by either (1) specifying an energy pathway for each country and having the model automatically compute sulfur emissions, or (2) bypassing the energy systems of each country and instead prescribing sulfur emissions for each country.

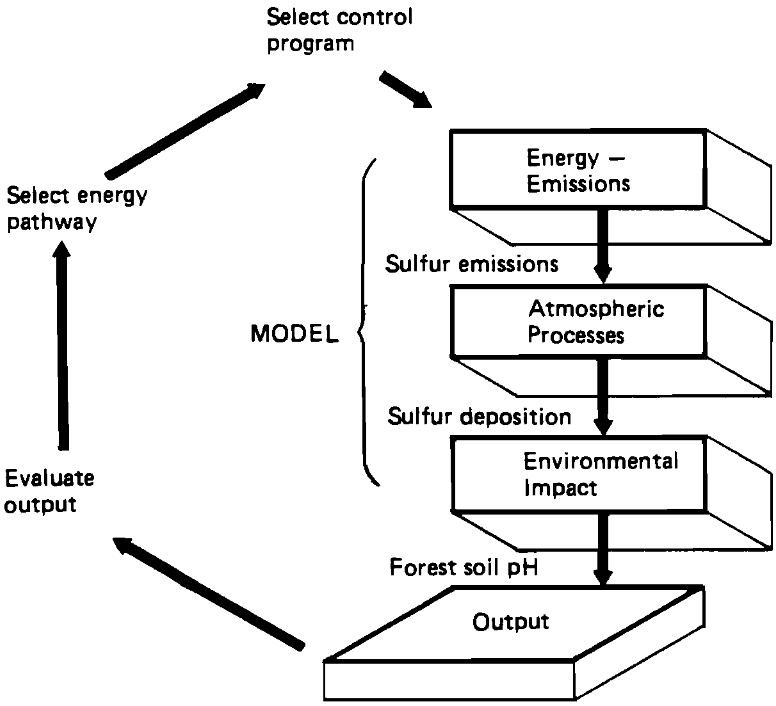


Figure 2-3. Procedure for using the model.

The decision maker also has a choice of two *impact indicators*, either annual sulfur deposition or forest soil pH.

In example 1 of Figure 2-4, the model user begins the analysis by selecting energy pathways for each country and then selects sulfur deposition as an indicator. In example 2, he/she prescribes the sulfur emissions of each country and uses forest soil pH as a damage indicator.

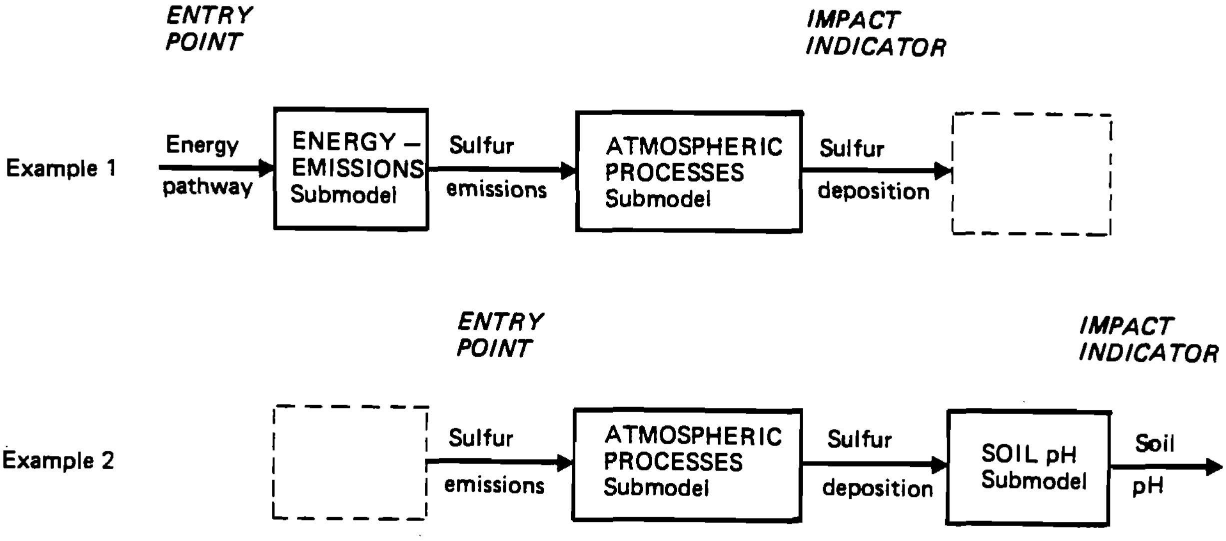


Figure 2-4. Flexibility of model use.

CHAPTER THREE

CURRENT SUBMODELS

This chapter describes the current status of the three submodels which comprise the IIASA Acid Rain Model.

ENERGY-EMISSIONS SUBMODEL

SUBMODEL PURPOSE

The purpose of the Energy-Emissions submodel is to compute sulfur emissions in each European country based on (1) estimated energy use in each country and (2) assumptions about fuel characteristics such as heat value and sulfur content. The model was designed to meet the following requirements:

1. Forecast sulfur emissions in each European country assuming no pollution control, i.e. a reference case of *no action*.
2. Evaluate effectiveness of major policies in each European country in reducing their sulfur emissions.
3. Provide a basis for assessing the costs of pollution control as part of a cost-benefit study.
4. Permit refinement of current estimates of sulfur emissions for each country.

5. Compute past sulfur emissions so that the other submodels (atmospheric processes and soil pH) can be tested against historical data.

Before proceeding with a description of this submodel a brief review of some important aspects of the sulfur emission problem in Europe is presented.

BACKGROUND

Any analysis of the acid rain problem in Europe must eventually turn to the subject of sulfur emissions. It is well accepted* that most sulfur emissions in Europe originate from human-related activities. The magnitude of natural emissions within Europe is thought to be 10% or less of the magnitude of anthropogenic emissions (Semb, 1978). There is disagreement, however, over the relative contribution of non-fossil fuel related activities (for example, originating from sulfuric acid production) to total anthropogenic emissions. Semb (1981) maintained that non-fossil sulfur emissions were at most 10-20% of the total anthropogenic emissions in any European country. In comparison, OECD (1981) reported that non-fossil fuel sulfur emissions exceeded fossil fuel sulfur emissions in the Netherlands during 1974. However on a European-wide basis it is recognized that the overwhelming majority of total emissions originate in fossil fuel combustion.

There are a wide variety of approaches available to reduce these sulfur emissions. In this paper we term these *pollution control alternatives.*

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*See, for example Highton and Chadwick (1982), Semb (1978) and OECD (1981).

Among four of the most attractive (because of their cost, technical availability/feasibility or simplicity) are:

1. *Flue gas control devices* - These include a number of different devices which remove stack gases or particles after they are produced. Conventional wet scrubbers, are the most widely used devices of this category. Also included, though less frequently used, are dry limestone scrubbers.

2. *Fuel cleaning* - Included in this category are various ways to clean coal through physical or chemical means, and different types of distillate and residue oil desulfurization.

3. *Low Sulfur Power Plants* - Modifications of the combustion processes in power plants and industrial boilers provide another opportunity to remove sulfur emissions before they are emitted into the atmosphere. Among the most technically feasible of these processes are ***atmospheric*** and ***pressurised fluidized bed combustion***. In comparison to conventional coal-fired power plants which retain a nominal amount of sulfur in their ash, fluidized bed plants may retain up to 90% of the coal's sulfur in the solid residue of the combustion chamber.

4. *Low sulfur fuels* - The potential for using low-sulfur coal or oil to control sulfur emissions in Europe has not yet been explored in a comprehensive fashion. OECD (1981) pointed out the relatively small remaining reserves of low sulfur coal in Western Europe yet also noted the opportunity for low sulfur North Sea

oil to reduce sulfur emissions.

Table 3-1 summarizes some feasible sulfur removal efficiencies of these approaches.

Table 3-1. Sulfur removal efficiencies of pollution control alternatives

Sulfur Removal Technology	Sulfur Removal Efficiency %
Flue Gas Control Devices	85-95
Physical Coal Cleaning	10-40
Oil Desulfurization	
-Distillate Fuels	90
-Vacuum Residue	<80
Fluidized Bed Combustion	<90

SUBMODEL STRUCTURE

Energy Pathways

The submodel illustrated in Figure 3-1 was designed in accordance with the previously mentioned objectives. The following paragraphs present an overview of this system. For more detail and a complete list of model equations the reader is referred to another publication (Alcamo and Posch, 1984).

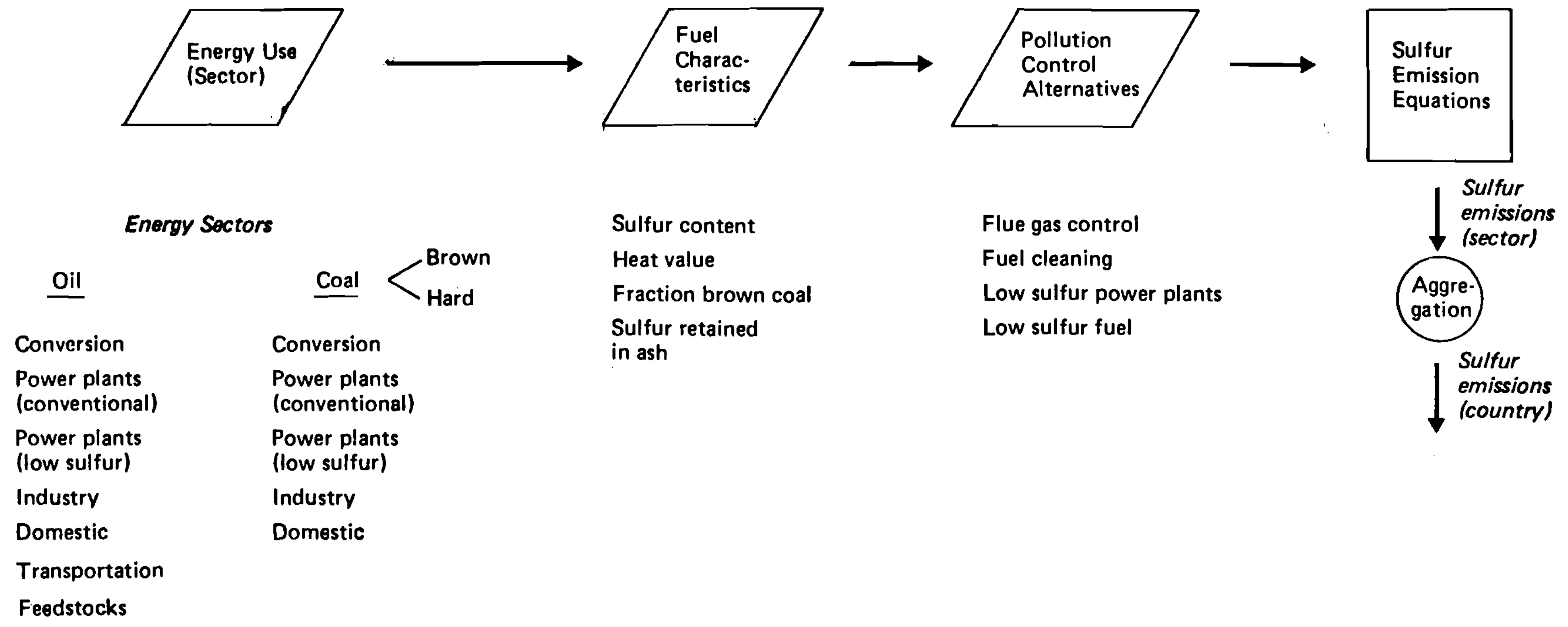

Figure 3-1. Schematic diagram of the energy-emissions submodel

The model user first prescribes certain energy pathways for each country. These energy pathways consist of energy use in each of 12 energy sectors for each country (Figure 3-1). This is the most appropriate disaggregation of European energy sectors according to their importance in producing sulfur.

Table 3-2. Countries in data base of energy emissions submodel.

Albania
Austria
Belgium
Bulgaria
Czechoslovakia
Denmark
Finland
France
Federal Republic of Germany
German Democratic Republic
Greece
Hungary
Ireland
Italy
Luxembourg
The Netherlands
Norway
Poland
Portugal
Romania
Spain
Sweden
Switzerland
Turkey
United Kingdom
Union of Soviet Socialist Republics
Yugoslavia

There are currently 27 countries contained in the data base (Table 3-2). Also there are two types of sulfur-producing fuel, coal and oil. Nonsulfur producing fuels are included for accounting purposes under the categories of *Natural Gas* and *Other*. The data base for 1960-1980 was taken from a variety of references. For 1980 to 2030, official ECE figures from ECE (1983) were adapted. ECE (1983) presents two scenarios:

- *Trends continued*
- *Conservation*.

The *Trends Continued* case covers from 1980 to either 1990 or 2000 depending on the country considered. Most European countries have their own *trends continued* data. The *Conservation* case is an energy scenario to the year 2000, aggregated into three European regions: (1) Western Europe, (2) Eastern Europe and (3) the USSR.

It was necessary to modify the ECE scenarios since they continue only to the year 2000 while model calculations extend to the year 2030. This was accomplished by assuming that energy use *in each sector* either (1) levels off, or (2) continues its trends after the year 2000. As a result, the model user has a choice of four *energy pathways* for each country. They are:

1. Trends continued, linear extrapolation;
2. Trends continued, leveling off;
3. Conservation, linear extrapolation
4. Conservation, leveling off.

Sulfur Emissions

Sulfur emissions are computed by multiplying fuel use in each sector (in petajoules) by the estimated sulfur content of the fuel taking into account the heat value of fuel and the amount of sulfur retained in the ash.

In any energy sector, k, the sulfur emissions (S_k) are related to energy use (E_k) by an equation of the form

$$S_k = E_k \cdot s_k^e \cdot p_k \cdot (1 - r_k) \tag{3-1}$$

where p_k is the fraction of sulfur removed by pollution control actions. The value of p_k is set to 1.0 when there is no pollution control. The variable r is the sulfur retained by a particular energy sector and not emitted to the atmosphere. This would account for the sulfur retained in the ash of power plants, for example.

Within this equation, the sulfur content of fuel (s^e) is given energy units. This is related to sulfur content of the fuel in weight units, s^w, and its heat value, h.

For oil this is simply

$$s^e(\text{oil}) = \frac{s^w}{h} \tag{3-2}$$

The sulfur content of coal in energy units accounts for two types of coal, hard and brown:

$$s^e(\text{coal}) = \left[f \cdot \frac{s^w}{h}\right]_{bc} + \left[f \cdot \frac{s^w}{h}\right]_{hc} \tag{3-3}$$

where the subscripts *bc and hc* refer to brown coal and hard coal, respectively, and *f* denotes the fraction of either brown or hard coal.

Substituting the above expression in equation (3-1), we obtain for each reference year and each coal sector *k*:

$$S_k(\text{coal}) = E_k \cdot \left[\frac{\left(f \cdot s^w\right)_{bc} + \left(f \cdot s^w\right)_{hc}}{\left(f \cdot h\right)_{bc} + \left(f \cdot h\right)_{hc}} \right] \cdot p_k \cdot (1 - r_k) \qquad (3\text{-}4)$$

For each oil sector the emission equation reads

$$S_k(\text{oil}) = E_k \cdot \frac{s^w}{h} \cdot p_k \cdot (1 - r_k) \qquad (3\text{-}5)$$

The total sulfur emissions for each country S_i consists of the sum of the contributions of oil and coal in all sectors plus the contribution of non-fossil fuel sulfur sources:

$$S_i = \sum_{k=1}^{n} S_k(\text{coal}) + \sum_{k=1}^{n} S_k(\text{oil}) + S_i(\text{non-fossil fuel}) \qquad (3\text{-}6)$$

Since there are 27 countries with 12 fossil fuel sectors in each country, we must solve equations (3-4) and (3-5) 324 times for each reference year.

Pollution Control Alternatives

The model user can now adjust these sulfur emission estimates to account for a pollution control program. There are currently four alternatives available to the user for controlling sulfur emissions. They are:

(a) Flue gas control devices.

(b) Fuel cleaning

(c) Low Sulfur Power Plants

(d) Low sulfur fuel

a. Flue Gas Control Devices

The model user can specify that a certain fraction of sulfur will be removed from the power plant and industrial sectors in a particular country by flue gas control devices. The user can also specify that pollution control devices will be installed on all new power plants or industrial boilers after a particular reference year. The user need only specify:

- The energy sector
- The removal efficiency of pollution control devices
- The reference year

The model will then compute the percentage of power plants and industrial boilers which have been constructed after the specified reference year and assigns the prescribed sulfur removal to this fraction. These computations assume that power plants have a 30 year lifetime.

b. Fuel cleaning

Removal of sulfur by fuel cleaning includes physical or chemical cleaning of coal or oil desulfurization. The model user has two options for accomplishing fuel cleaning:

(1) Specify the fraction of sulfur removed in each sector by fuel cleaning or,

(2) Specify that a certain sulfur content objective will be accomplished. For example, a user may indicate that all coal in the domestic sector will be cleaned down to a 1% sulfur content.

c. Low Sulfur Power Plants

As a method for controlling sulfur emissions, the user may specify that a certain fraction of power plants are low sulfur power plants. Power plants with fluidized bed combustion chambers are one example of low sulfur producing plants. The user may also specify that all new power plants after a reference year will be low sulfur producing power plants. In this case, the model automatically computes the fraction of power plants after the specified reference year which are low sulfur plants.

d. Low Sulfur Fuel

The remaining option concerns the use of low sulfur coal as a pollution control alternative. The user has two options for this strategy:

1. He/she can specify that a certain percentage of the coal in a particular sector will be low sulfur coal. In this case the sulfur content of this coal must also be specified.
2. The user may also specify that a certain fraction of the total coal in a country will be low sulfur and then list the priority of sectors to which this coal will be allotted to. For example, a model user may specify that one quarter of the coal in country

A in reference years 2000, 2010, 2020 will be low sulfur coal with a sulfur content of 0.8%. The model will then allocate the specified amount of low sulfur coal to the sectors in the priority called for by the user.

SOURCES OF UNCERTAINTY IN THE ENERGY-EMISSIONS SUBMODEL

Uncertainty due to Model Structure refers to errors resulting from an imperfect or inaccurate representation of reality by a model. In the case of the Energy-Emissions submodel this source of error is not too great because sulfur emissions are computed in a very straightforward fashion, based on the principle of conserving mass. This approach takes into account all sulfur emitted in Europe other than natural emissions. Neglecting natural sulfur emissions may result in underestimating total sulfur emissions in Europe by 10%.

Parameter uncertainties arise from inaccuracy of estimating model parameters. The variable r_k which describes the sulfur retained in "ash" rather than emitted by each combustion process, is not expected to vary too much throughout Europe. Since this variable is relatively easy to measure, it is a source of "reducible" uncertainty.

The heat value of fuel, h, does not vary very much for either hard coal or oil because of the nature of this fuel. The heat value of brown coal however, varies by a factor of 3 or 4 throughout Europe. Fortunately country-wide estimates of brown coal heat value are available from official statistics.

The parameter which describes the fraction of brown coal to total coal in a country, f_{bc}, should not radically change in the near future if we can assume that countries which possess brown coal will continue to exploit it at their current rates. As an example, the historical stability of this parameter in two countries is illustrated in Figure 3-2.

The model parameter with greatest uncertainty is s_w, the sulfur content of fuel in weight units. This parameter can vary from process to process, country to country and year to year. Improvements in forecasting sulfur emissions should focus on improving the accuracy of estimating this parameter.

The final category of submodel uncertainty *is uncertainty due to changes in the driving functions of the submodel.* In the case of the Energy-Emissions submodel, the driving function is the expected energy used in each sector in each country during the 50 year model time horizon of the model. We make this uncertainty explicit by giving the model user a choice of four possible energy pathways for the future. Considering the high degree of uncertainty in forecasting energy use, this may be the best way of dealing with this uncertainty in the acid rain model.

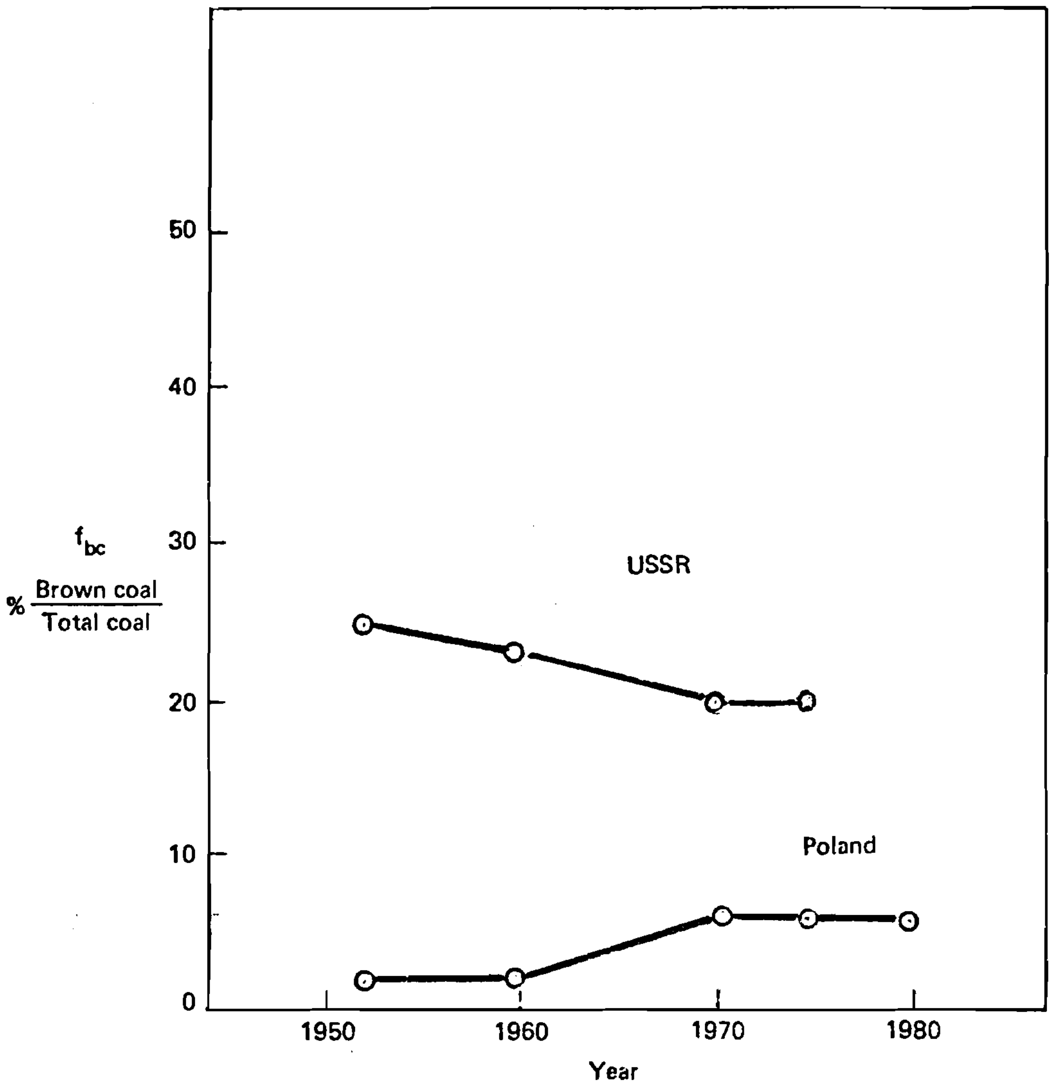

Figure 3-2. Percentage of total coal production that was brown coal in USSR and Poland, 1950-1980.

ATMOSPHERIC PROCESSES SUBMODEL

SUBMODEL PURPOSE

The Atmospheric Processes submodel serves as the link between sulfur emissions in each country and their impact on the environment. The following guidelines were used in its selection. It must:

1. Compute sulfur deposition patterns throughout Europe.
2. Evaluate the fraction of sulfur deposition at any location in Europe due to a single country or group of countries.
3. Be relatively simple computationally.

The following section reviews some important aspects of transport, transformation and deposition of air pollutants which are relevant to the selection of the Atmospheric Processes submodel.

BACKGROUND

Once sulfur is emitted to the atmosphere, it undergoes several complex physical and chemical processes before wet and dry deposition return it to the ground. Without removal, the concentration of sulfur dioxide in the atmosphere would increase at the constant rate of about 70 μgS m^{-3}/ year . Comparing this with the annual US standard for SO2 which is of 40 μgS m^{-3}, we realize the importance of dry and wet deposition in avoiding accumulation of sulfur in the atmosphere. Unfortunately, deposition of sulfur compounds is one of the major causes of the acidification of the environment. Therefore, in order to generate "acid rain" control scenarios we must relate spatial and temporal patterns of sulfur deposition to emission rate and distribution. This task, especially if conducted over an area as large as Europe, presents great complexity and difficulty.

The majority of sulfur released to the atmosphere is in the form of sulfur dioxide; only a minimal amount is emitted directly as sulfate. If we neglect this fraction, the fate of anthropogenic sulfur dioxide can be represented by the simplified diagram of Figure 3-3.

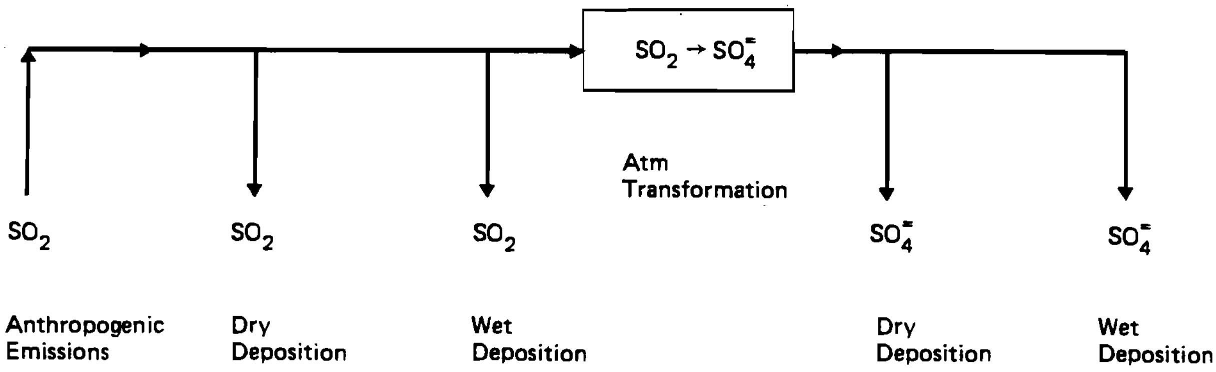

Figure 3-3. Simplified cycle of atmospheric sulfur oxides.

The time scales of these processes have been discussed by Rodhe (1978) for European conditions. The atmospheric lifetime of SO_2 and $SO_4^=$ is in the order of 1-2 and 3-5 days respectively. Approximately 30% of SO_2 is converted to $SO_4^=$ before being deposited. Deposition and transformation rates depend on factors of meteorology, climate and topography. Transformation of sulfur dioxide to sulfate also depends on the concentration of oxidizing compounds which in turn depends on the concentration and interaction of other pollutants, such as NO_x and hydrocarbons. Since deposition patterns of sulfur compounds are determined by their rates of deposition and transformation, the selection of these rates is one of the major challenges of modeling long-range transport of sulfur.*

Deposition and transformation processes occur while sulfur dioxide and sulfates are transported by the wind and dispersed by atmospheric turbulence. The interaction of deposition and transformation with transport and dispersion processes is very complex. For a discussion of this interaction, the reader is referred to Lamb (1983).

SUBMODEL STRUCTURE

Some of the processes which affect long range transmission of air pollutants have been introduced above. If a refined spatial and temporal resolution of deposition patterns is required, these processes must be properly parametrized and included in a model. This parametrization greatly depends on the availability of a date base with the required level of accuracy and resolution, both in time and space. Very advanced models are in development at various institutes, and they will hopefully be able to incorporate most or all of the relevant processes. Once they become available, they will be included in the IIASA system of models. However, satisfactory results are achieved for coarse spatial and temporal resolution by the simplified parameterization developed within the

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*See for example Eliassen and Saltbones (1975).

OECD–LRTAP programme (see Ottar, 1978 and Eliassen, 1978).

The long-range model operated within EMEP is of the Lagrangian type. A full discussion of this model is given by Eliassen and Saltbones (1983). Fisher (1984) and Lamb (1984) describe the context of this model within current practice of long-range modeling. Below we summarize the basic concepts on which this model is based, and describe how it has been adapted as a submodel for the IIASA acid rain model.

The EMEP model predicts concentrations of sulfur dioxide and sulfate at the center of 150 km grid elements. Every 6 hours air trajectories are computed backward from the center of each grid element and are followed for 96 hours. The model then solves the mass balance equation for sulfur dioxide and sulfate along each trajectory. The model assumes uniform mixing of the sulfur released from each grid element up to the mixing height. The mixing height is constant and equal to 1000 m. In practice, two one-dimensional equations are solved along each trajectory. These equations have the form:

$$\frac{dC_{SO2}}{dt} = \text{Source}_{SO2} - \text{Sink}_{SO2} \qquad (3\text{-}7)$$

$$\frac{dC_{SO4^=}}{dt} = \text{Source}_{SO4^=} - \text{Sink}_{SO4^=} \qquad (3\text{-}8)$$

where C indicates concentration in sulfur units. For the above assumption the source term for SO_2 is given by:

$$\text{Source}_{SO2} = \gamma \frac{Q}{h} \qquad (3\text{-}9)$$

where Q is the SO_2 emission per unit area and time, h is the mixing height and γ accounts both for the part of SO_2 which is directly deposited in the grid element and for the small fraction of it directly transformed to $SO_4^=$. The source term for $SO_4^=$ can be written as:

$$\text{Source}_{SO4^=} = \beta \frac{Q}{h} + kC_{SO2} \tag{3-10}$$

where β is the fraction of the SO_2 directly transformed to $SO_4^=$ and k is the transformation rate $SO_2 \rightarrow SO_4^=$.

Both Sink_{SO2} and $\text{Sink}_{SO4^=}$ have the form:

$$\text{Sink} = \delta C \tag{3-11}$$

where δ is a suitable decay rate. Precipitation and dry deposition are taken into account by modifying δ.

The values of SO_2 and $SO_4^=$ concentration, computed by the above equations, are used to compute dry and wet deposition. Eliassen (1978) describes the parameterization which has been adopted to compute deposition.

Deposition and concentration values given by the model are assumed to be an *estimate* of the real values which occur at the center of the grid elements every six hours. Because of the above simplifying assumptions, satisfactory results can be obtained only if the values simulated by the model are used to compute long-term averages so that data and assumption inaccuracies are smoothed out (see Eliassen and Saltbones, 1982). Accordingly, in the present study we have used only annual averages. In addition, annual sulfur deposition corresponds to the needs of our forest soil pH submodel, which is described in the next section of this paper.

The application of a Lagrangian model requires the computation of air trajectories. The choice of a wind for the computation of the air trajectory along which pollutants are transported is to some extent arbitrary. However for long-term averages (monthly or longer), model results are not very sensitive to the choice of the advection wind (Eliassen and Saltbones, 1983). The trajectories of the EMEP model are obtained by using the wind at 850 mb.

The EMEP long-range model is too demanding computationally (in terms of data and time) to be used directly as a submodel of the IIASA acid rain model. To make it usable in our analysis we have reduced it to a "source receptor matrix", schematically represented in Figure 2-2 of Chapter 2.

The rows of the source-receptor matrix correspond to European countries and the grid elements refer to the grid elements illustrated in Figure 3-4. The scenarios discussed in this paper are based on the source receptor matrix of a two-year simulation run, using 1978-79 data.

In practice, the source-receptor matrix is linked to the Energy-Emissions submodel as follows. The Energy-Emissions submodel computes sulfur emissions for a particular country. These sulfur emissions are then distributed to different grids of the source-receptor matrix in proportion to their current (1978-79) distribution. These sulfur emissions are then converted by the source-receptor matrix to total (i.e. dry plus wet) annual sulfur deposition in each grid square throughout Europe. Figure 3-4 illustrates the grid used by the submodel. The Atmospheric Processes submodel then interpolates between computed sulfur deposition values to create sulfur deposition maps shown in Figures 4-5, 4-10 and 4-13 of Chapter 4. Figure 3-5 summarizes the operation of this submodel.

SOURCE OF UNCERTAINTY IN ATMOSPHERIC PROCESSES SUBMODEL

The uncertainty of the Atmospheric Processes submodel depends to a great extent on the uncertainty of the EMEP model upon which it is based.

A major source of uncertainty is due to ***model structure***. The uncertainty connected with the structure and development of a long-range model is discussed in detail by Lamb (1983).

Another major source of uncertainty is due to the variation of ***model parameters***. These parameters include:

- fraction of sulfur deposited in each grid element due to emission in the grid element
- fraction of sulfur directly emitted as sulfate
- sulfur dioxide transformation rate to sulfate
- sulfate decay rate
- transformation of air concentration to deposition rate
- height of the mixing layer

Apart from uncertainty due to model structure and model parameters, the variability of input data also adds uncertainty to the results of the EMEP model. This includes errors in estimating wind and precipitation patterns in addition to variability in location and magnitude of sulfur emissions.

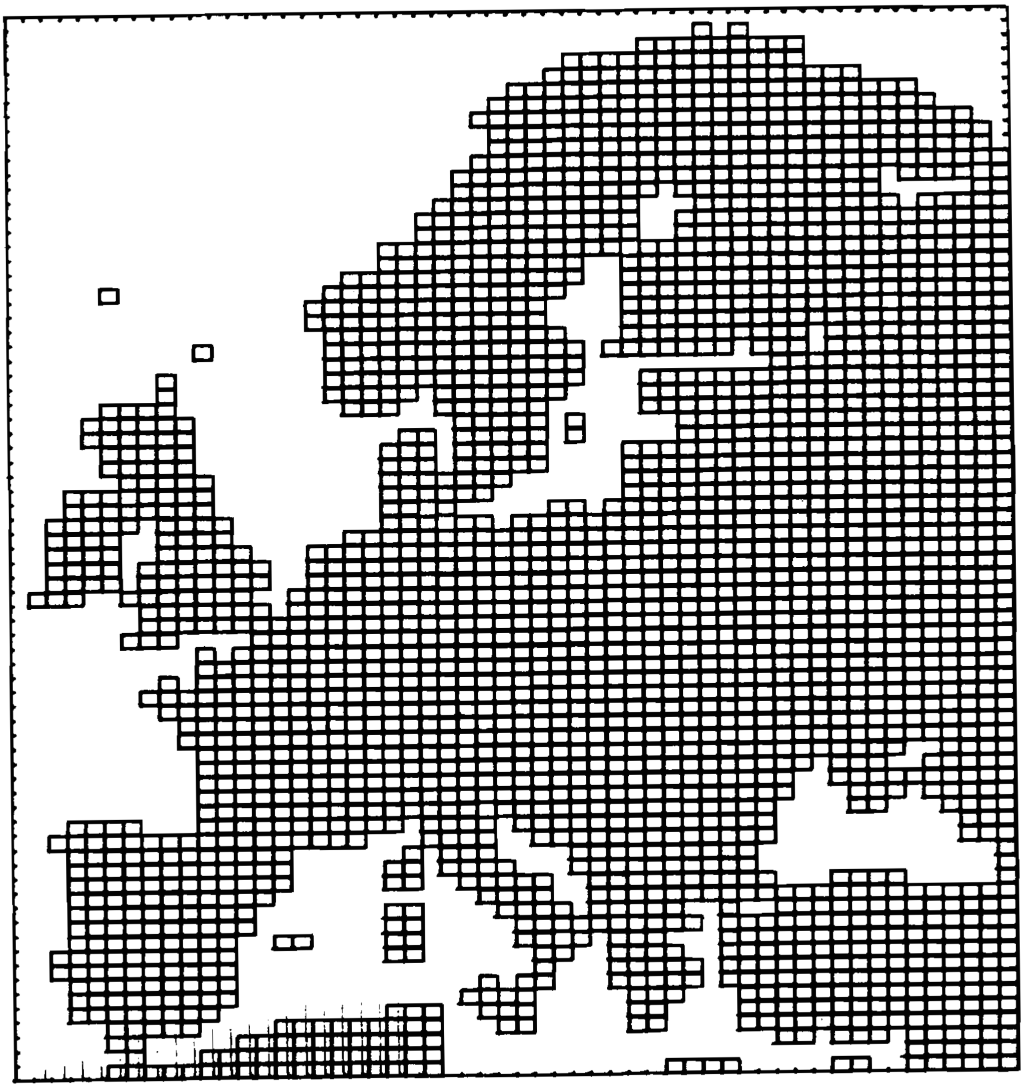

Figure 3-4. Grid of Europe used by atmospheric processes submodel.

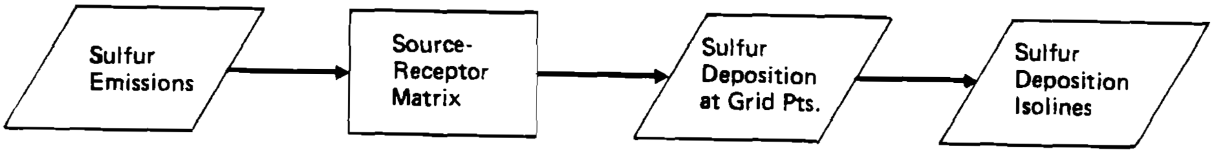

Figure 3-5. Schematic diagram of atmospheric processes submodel

FOREST SOIL PH SUBMODEL

MODEL PURPOSE

The purpose of this submodel is to convert sulfur deposition estimates into approximations of forest soil pH. The output information is then interpreted in terms of risk of forest damage. Models were not found in the literature which would fulfill this purpose for the large spatial scale of the IIASA study. An in-house model was therefore constructed with collaboration of Dr. Egbert Matzner from the University of Göttingen, FRG. A detailed report of the model is in press (Kauppi et al. 1984).

BACKGROUND

Extensive forest damage in rural areas has been observed in Central Europe since the 1970's. Air pollution is generally considered a major cause of this damage. Two physiological pathways have been identified: (i) Direct intake of pollutants through the leaves with the subsequent decline of photosynthetic productivity; and (ii) Root damage due to unfavourable changes in the soil. Soil acidification is associated with the latter pathway.

Accumulation of H^+ ions leads to low pH in the soil solution; it is thus appropriate to define ***acid stress*** as the input of H^+ ions into the top layer of soil. The acid stress has two important aspects. One is the cumulative load of the stress and the other is the instantaneous rate of the stress. The variable amount of stress refers to the load, and involves accumulation over several years. The unit for the amount of stress is kiloequivalents of acidity per hectare (keq ha^{-1}). ***Stress rate*** refers, in principle to the rate of change of the ***amount of stress***, although in practice it is given as annual input. The unit for the ***stress rate*** is kiloequivalents of acidity per hectare and year (keq $ha^{-1}yr^{-1}$).

Soil reacts to the acid stress depending on its soil characteristics. A certain level of acid stress may produce a substantial decline of soil pH in one type of soil and no change in another soil type. Such difference result from the buffering properties of the soil. Buffering implies consumption of protons, which tends to stabilize the soil pH. Also, buffering is described by two variables, one for the gross potential and the other for the rate of the reaction.

Buffer capacity is the total reservoir of the buffering compounds in the soil. and has the same units as acid stress: kiloequivalents of acidity per hectare (keq ha^{-1}). ***Buffer rate*** is defined as the rate at which protons react with buffering compounds and can be expressed in units comparable to those of the stress (keq $ha^{-1}yr^{-1}$).

A model to compute soil pH on a regional basis in Europe must incorporate both acid stress and the buffering properties of the soil.

SUBMODEL STRUCTURE

An overview of the Forest Soil pH submodel is presented in Figure 3-6. Based on input from the Energy-Emissions submodel, the Atmospheric Processes submodel computes annual sulfur deposition throughout Europe with a spatial resolution of 150 by 150 kilometers. Total sulfur deposition is converted in the soil pH submodel to an equivalent deposition of hydrogen ions assuming that acid deposition enters soil solution as sulphuric acid. It is assumed, as a first approximation, that sulfur deposition is the dominant net contributor to acid stress. This approximation is discussed further in Kauppi et al. (1984).

Buffering processes involve a large number of chemical reactions. These buffering processes in soil have been systematically described by Ulrich (1981, 1983). Discrete categories, called ***buffer ranges***, are used to indicate the dominant chemical reactions. Each buffer range has a characteristic soil pH (Table 3-3). The name of each buffer range refers to the dominant buffer reaction.

Table 3-3. Classification of the acid buffering reactions in forest soils.

Buffer Range	Typical pH
Carbonate buffer range	8.0-6.2
Silicate buffer range	6.3-5.0
Cation exchange buffer range	5.0-4.2
Aluminium buffer range	4.2-3.0
Iron buffer range	<3.8

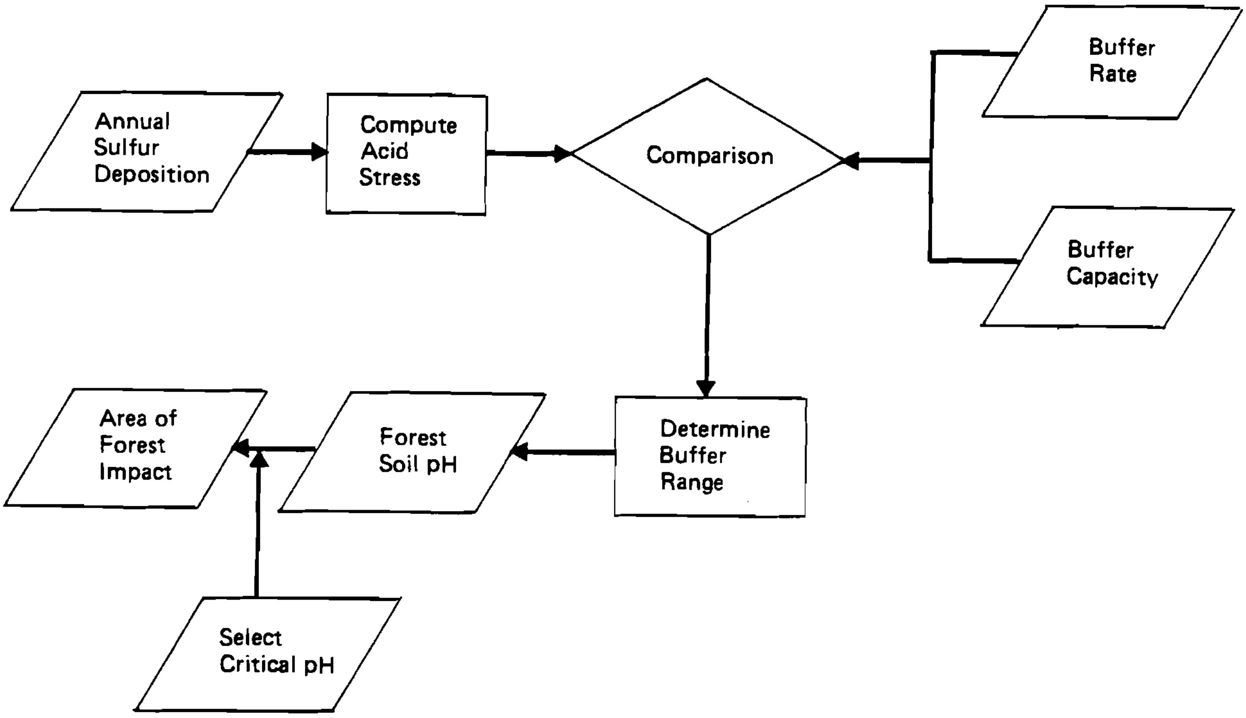

Figure 3-6. Forest soil pH submodel.

To use the model it is necessary to input buffer rates and buffer capacities for the buffer ranges in Table 3-3. Buffer capacity of the carbonate range, for example, is proportional to the lime content of the soil. Although quantitative relationships of this type are only partially understood, they are a useful first approximation for quantifying the susceptibility of the soils to acidification. Data values for the description of the soil variables were obtained from the FAO/UNESCO Soil Map of the World and other sources (for details, see Kauppi et al. 1984).

All information regarding the soil was stored in a computerized grid-based format. Each grid square covered 1 degree longitude and 0.5 degrees latitude. The size of a grid square was fixed at 56 km in the south-north direction, but varied from 91 km to 38 km in the east-west direction depending on the latitude. The number of the grid squares was 2473.

Before running the model the values of buffer capacity and buffer rate must be initialized. This initialization should be based on extensive measurements, though for the time being, the initialization had to be based partially on expert judgement. The year 1960 was selected as the base year.

The model was built to compare on a grid basis (i) the value for the amount of stress (cumulative value over the time period of interest) to the value for the buffer capacity, and (ii) the value for the stress rate (year-to-year basis) to the value for the buffer rate. With these comparisons the program calculates which buffer range prevails each year, and then converts this information into an approximation of the prevailing soil pH in that grid square. In this way the model produces pH scenarios for European forest soils. The results are interpreted in relation to the potential forest damage by assigning a *critical soil pH level*, below which forest damage is assumed to occur. Some scientists have suggested that an appropriate critical pH is 4.2, since concentrations of toxic elements in the soil solution greatly increase when soil is more acid than this. The definition of the critical level, however, is left to the model user.

The model user has two options to display model output. One option indicates the area below the critical pH in a map format (see Figures 4-7, 4-11, or 4-14 in Chapter 4, for example) and may be interpreted as the location of high risk. The other option displays the time development of the area of forest soils below critical pH. This option is calculated by taking into account the fraction of forest land in each grid square.

SOURCES OF UNCERTAINTY IN THE FOREST SOIL PH SUBMODEL

Uncertainty due to the model structure. Forest damage, and even the risk of forest damage, is a multicausal phenomenon. Isolating the soil pH from other factors such as the pollution due to ozone or heavy metals, or climatic factors, omits a part of the problem. Species differences are currently not included; though later such differences could be implemented into the model by introducing pH response functions which are species specific.

Biomass utilization (timber removal and logging) causes a substantial flux of ions out of the forest ecosystem. It tends to add to the acid stress of air pollution. Accumulation of biomass in the ecosystem, such as through peat or humus formation has a similar effect. The model can account for these factors by adding them into the value of acid stress, grid by grid. However, data were not available for accomplishing this task. Therefore, the results tend to overestimate the soil pH especially in northern Europe where, for climatic reasons, the accumulation of the biomass is the dominant phenomenon.

A simple step-function was selected to relate the risk of forest damage to the soil pH. Below a *critical pH level* all soils were assumed to exhibit the full risk whereas above the threshold no risk was assumed. This step-function could be replaced with a more realistic s-shaped function once more data become available.

All soil layers were assumed to respond equally to the acid stress. In reality, there is a vertical gradient of acidity in soil, with the highest acidity occurring in the top layer.

All deposition was assumed to react with the top soil. However, part of the stress passes this layer either by percolating deeper into the soil or by passing over the soil dissolved into the surface water.

Uncertainty due to Model Parameters. A depth of 50 cm was selected to determine the volume of the reacting soil. The values for the buffer capacity and buffer rate were adjusted accordingly. If the layer is fixed at 1 meter then the values must be doubled. Values for the buffer capacity and buffer rate were initialized for the year 1960. A detailed sensitivity analysis regarding these initial values is being conducted.

Input Uncertainty. Sulfur deposition was used to estimate the acid stress. This approximation is derived empirically and the validity of the estimates are dependent on ambient conditions. More information is needed to improve the estimate of acid stress, including the fraction of sulfur compared to other pollutants. Other uncertainty includes the possible difference in the amount of sulfur deposition into forest vs. agricultural land. The model used to relate sulfur emissions to sulfur deposition uses a single value for deposition velocity over all land surfaces. Yet it has been observed that forest ecosystems absorb pollutants more effectively than other land surfaces. Therefore, averaging over all land surfaces tends to underestimate the deposition into forests. This may result in a secondary feedback. If forests are damaged they may exhibit weakening capability of absorbing the pollutants. This would add to the pollutant concentrations of the down-wind areas and in this way accelerate the damage.

Evaluation of the Sources of Uncertainty. An assessment is being made to rank the sources of uncertainty so that the most important sources of uncertainty can be quantitatively evaluated. This evaluation will explicitly express the uncertainty of the submodel and may lead to model improvements.

The relative importance of the various sources depends in part on how the model is applied. In general, the longer the time period in the simulation the larger will be the uncertainty.

Two other sources of uncertainty are particularly critical in many applications. One is that risk of forest impact is not affected by the soil pH alone. Another is that biomass utilization and so-called internal proton production of ecosystems are certainly of importance in determining soil acidity. A third source, enhanced deposition velocities of forest areas, may be of importance especially in areas near to pollution sources.

CHAPTER FOUR

USING THE MODEL

As emphasized in preceding chapters, the model has been designed for easy handling by non-technical users. Chapter 2 and Figure 2-3 provide an overview of this use. Chapter 3 describes the structure of the submodels which make up the model so that users can understand the assumptions behind the model's computations. The current chapter explains in more detail the procedure for using the model.

In practice, each session of model use begins with the user sitting in front of two computer terminals each with its own screen. On one screen, he/she sees the questions which the computer poses in order to obtain needed input for running the model. On another screen, the user can see the information provided by the model. Appendix A presents the input of a sample interactive session. We now present three examples of how the model is used in practice.

EXAMPLE 1 Examining the Consequences of a Particular Energy Pathway

To summarize our first example, a model user first selects one of four possible *energy pathways*. Next the model computes sulfur emissions in each country for several reference years between 1980 and 2030. The user can then examine the impact of these emissions on either sulfur deposition or forest soil pH throughout Europe.

This is how the session proceeds step-by-step: The user selects one of the following four *energy pathways* which are defined in Chapter 2 and described further in Chapter 3:

1. Trends Continued – Linear Extrapolation
2. Trends Continued – Leveling Off
3. Conservation – Linear Extrapolation
4. Conservation – Leveling Off

After selecting a pathway, the user may examine the data base of this pathway for a single country or a group of countries. In Figure 4-1, we have assumed for illustration that the model user has selected Energy Pathway No. 4. Notice these data are arranged according to year and energy sector. As an alternative, he/she may examine the graphical summary of these data shown in Figure 4-2.

While the user examines the energy data, the model computes the sulfur emissions in each country between 1990 and 2030 resulting from the selected energy pathway. The user can now examine a detailed tabulation of sulfur emissions for an individual country or totaled for Europe. Figure 4-3 notes that these data are arranged in the same way as the energy data. The user also may see the graphical summary of these data presented in Figure 4-4.

Now the user must select either sulfur deposition or forest soil pH as an *impact indicator* (defined in Chapter 2) for evaluating the impact of the selected energy pathway. Note, however, that the user may examine both indicators. If sulfur deposition is selected, the user must then specify – (1) a country or group of countries; (2) one or more isolines, i.e., lines of equal value of sulfur deposition; and (3) a year. As an example, the user obtains the results in Figure 4-5 by specifying

(1) the contribution of all European countries to sulfur deposition

(2) the 0.5 and 2.0 $g \cdot m^{-2} \cdot yr^{-1}$ isolines of total annual sulfur deposition

(3) the year 2010

These results pertain to energy pathway No. 4 originally selected by the user.

An additional option of the model permits the user to evaluate the sources of sulfur deposition at any point in Europe for any year desired. Let us assume that a model user wishes to know the source of sulfur deposition at a location in central Hungary for the year 2010. The user must input -- (1) the latitude and longitude of the receptor location, and (2) the year. The model responds with a breakdown of contributing countries illustrated in Figure 4-6.

We now proceed with the final impact indicator -- forest soil pH. To examine forest soil pH as an impact indicator, the user must specify -- (1) a critical pH level, and (2) a year. The concept of ***critical pH*** is discussed in Chapter 3. For illustration, we assume the user has specified a critical pH of 4.2 and the year 2010. The computer responds with Figure 4-7 which depicts the area computed to have a forest soil pH less than 4.2 in the year 2010 due to energy pathway No. 4.

Energy data (PJ) for EUROPE

	total	coal					
		PRIM.	conv.	PPcnv	PPlow	Dom.	Ind.
1960	70230.	38321.	7931.	12585.	0.	8077.	9728.
1970	133988.	40591.	7920.	15879.	0.	7444.	9348.
1974	156714.	40603.	7462.	17073.	0.	6748.	9320.
1980	181727.	42774.	7113.	20598.	0.	6362.	8701.
1985	199071.	45000.	8006.	22381.	0.	3628.	10986.
1990	204986.	46588.	8858.	22222.	0.	2677.	12832.
2000	216836.	40996.	9720.	20877.	0.	1530.	8868.
2010	216836.	40996.	9720.	20877.	0.	1530.	8868.
2020	216836.	40996.	9720.	20877.	0.	1530.	8868.
2030	216836.	40996.	9720.	20877.	0.	1530.	8868.

Energy data (PJ) for EUROPE

	oil								gas	other
	PRIM.	conv.	PPcnv	PPlow	Dom.	Ind.	Tran.	Feed.		
1960	26101.	14581.	850.	0.	2209.	3806.	3681.	974.	2666.	3143.
1970	76681.	42055.	3718.	0.	8024.	10625.	8836.	3423.	12205.	4510.
1974	92268.	50668.	4994.	0.	8973.	12197.	10850.	4586.	18669.	5174.
1980	104439.	56221.	9558.	0.	8822.	11826.	13403.	4608.	26080.	8434.
1985	105347.	57872.	9107.	0.	6542.	10884.	15877.	5065.	32740.	15983.
1990	102916.	58753.	7167.	0.	5479.	9039.	17133.	5345.	32135.	23347.
2000	100513.	58872.	3835.	0.	3335.	7938.	20955.	5577.	35866.	39461.
2010	100513.	58872.	3835.	0.	3335.	7938.	20955.	5577.	35866.	39461.
2020	100513.	58872.	3835.	0.	3335.	7938.	20955.	5577.	35866.	39461.
2030	100513.	58872.	3835.	0.	3335.	7938.	20955.	5577.	35866.	39461.

Figure 4-1. Energy data base for example 1.

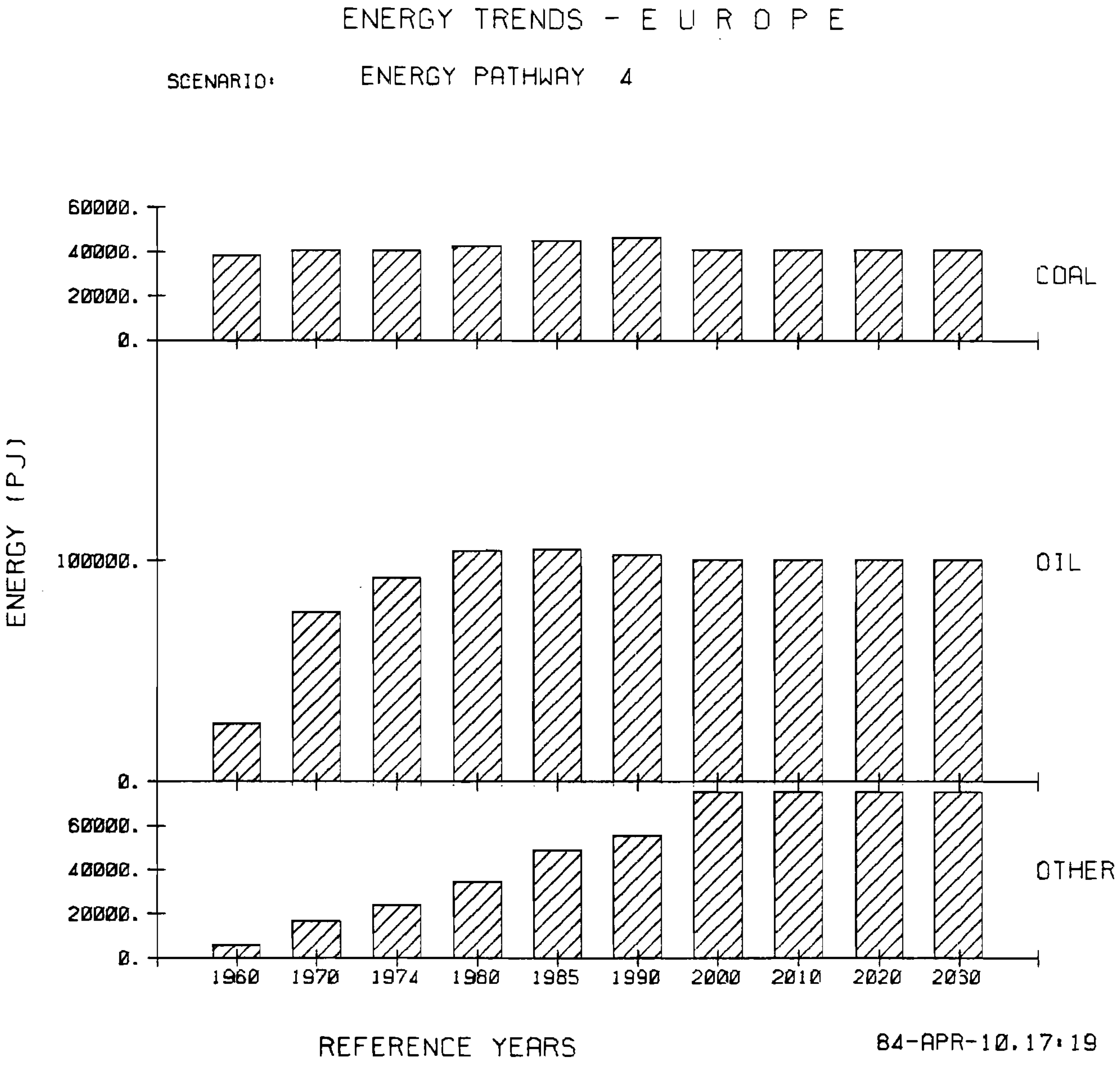

Figure 4-2. Graphical summary of energy data base for example 1 .

```
Total sulfur emitted (kt) in E U R O P E
--------------------------------------------------------------------
|    | total  |                      coal                          |
|----|--------|----------------------------------------------------|
|    |        | PRIM. | conv. | PPcnv | PPlow | Dom.  | Ind.  |
|----|--------|-------|-------|-------|-------|-------|-------|
|1960| 18515. |14792. |  877. | 6225. |    0. | 3410. | 4281. |
|1970| 27608. |16436. |  930. | 7884. |    0. | 3388. | 4233. |
|1974| 30222. |16733. |  882. | 8443. |    0. | 3196. | 4212. |
|1980| 34889. |17859. |  876. | 9997. |    0. | 3035. | 3950. |
|1985| 34469. |18371. |  942. |10624. |    0. | 1707. | 5098. |
|1990| 32644. |18570. | 1035. |10321. |    0. | 1252. | 5963. |
|2000| 27178. |15999. | 1092. |10128. |    0. |  713. | 4067. |
|2010| 27178. |15999. | 1092. |10128. |    0. |  713. | 4067. |
|2020| 27178. |15999. | 1092. |10128. |    0. |  713. | 4067. |
|2030| 27178. |15999. | 1092. |10128. |    0. |  713. | 4067. |
--------------------------------------------------------------------
```

```
Total sulfur emitted (kt) in E U R O P E
-----------------------------------------------------------------------------
|    |                              oil                                      |
|----|-----------------------------------------------------------------------|
|    | PRIM. | conv. | PPcnv | PPlow | Dom.  | Ind.  | Tran. | Feed. |
|----|-------|-------|-------|-------|-------|-------|-------|-------|
|1960|  3723.|  937. |  480. |    0. |  583. | 1595. |  100. |   27. |
|1970| 11172.| 2550. | 1966. |    0. | 1900. | 4428. |  240. |   89. |
|1974| 13489.| 3105. | 2705. |    0. | 2213. | 5048. |  299. |  118. |
|1980| 17031.| 3556. | 5724. |    0. | 2372. | 4879. |  374. |  125. |
|1985| 16098.| 3664. | 5388. |    0. | 1759. | 4700. |  442. |  145. |
|1990| 14074.| 3667. | 4262. |    0. | 1484. | 4025. |  480. |  156. |
|2000| 11178.| 3624. | 2332. |    0. |  929. | 3541. |  585. |  167. |
|2010| 11178.| 3624. | 2332. |    0. |  929. | 3541. |  585. |  167. |
|2020| 11178.| 3624. | 2332. |    0. |  929. | 3541. |  585. |  167. |
|2030| 11178.| 3624. | 2332. |    0. |  929. | 3541. |  585. |  167. |
-----------------------------------------------------------------------------
```

Figure 4-3. Computed sulfur emissions for example 1 .

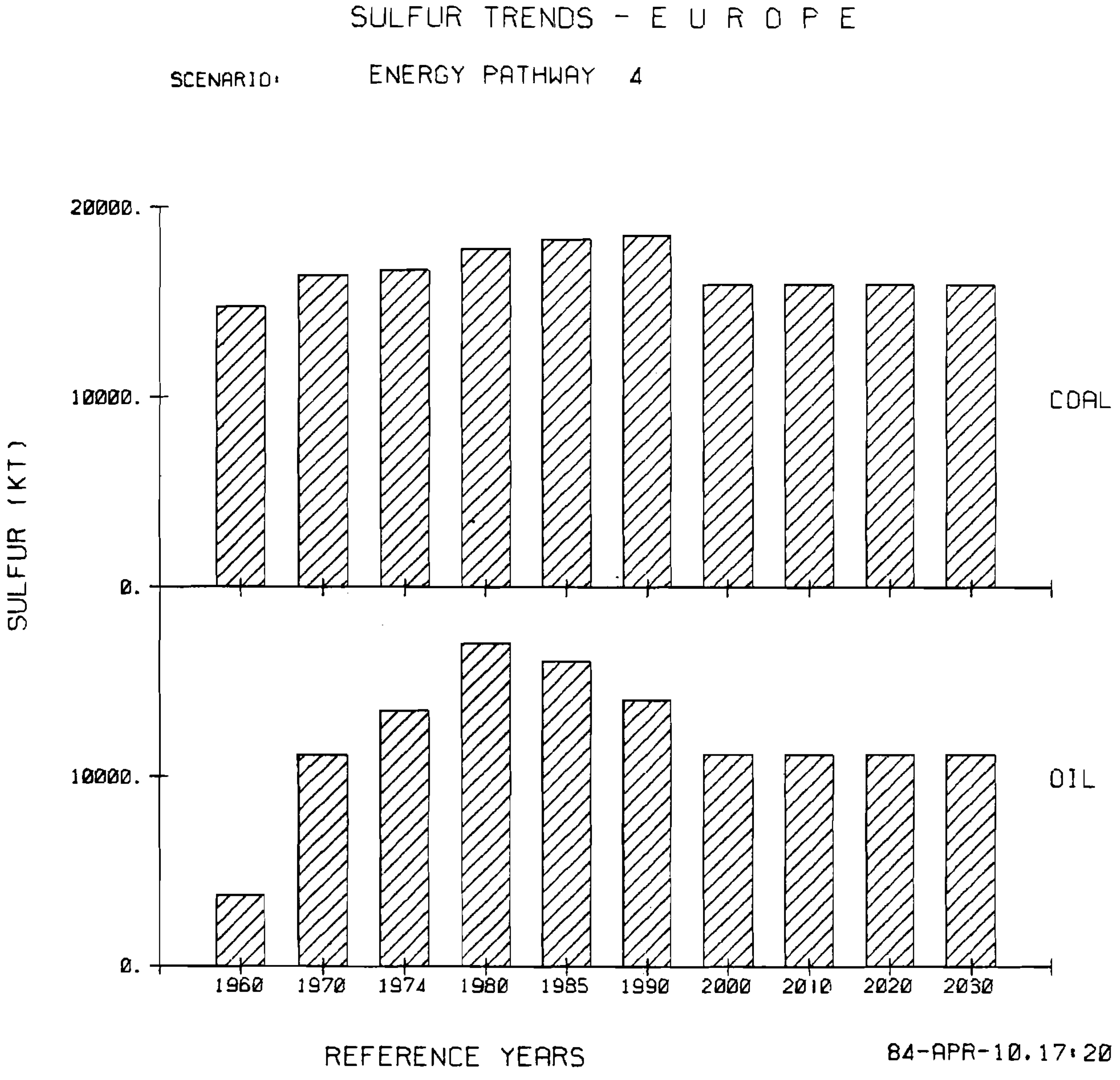

Figure 4-4. Graphical summary of computed sulfur emissions .

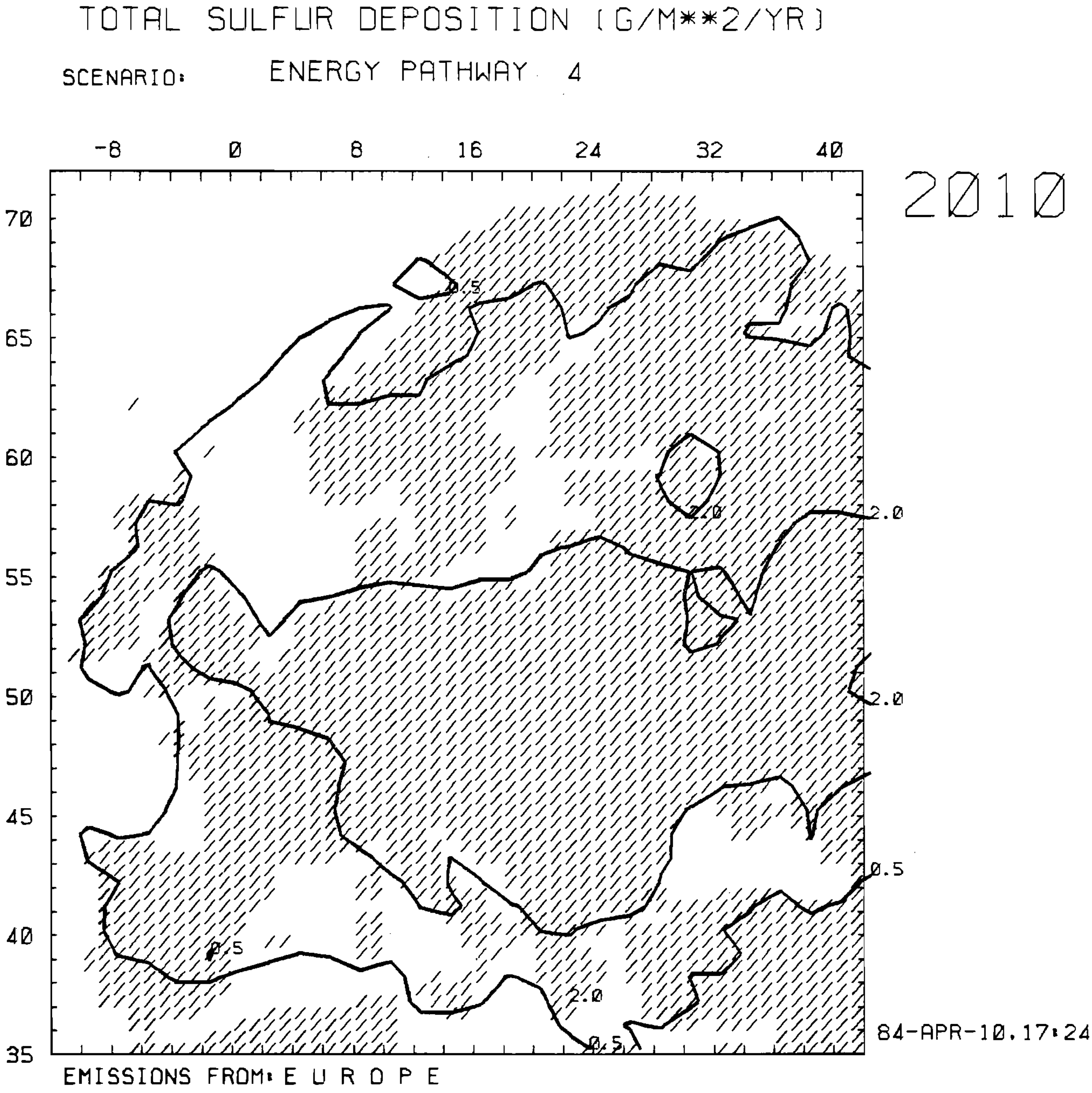

Figure 4-5. Total sulfur deposition in the year 2010 computed in example 1. The isolines of 0.5 and 2.0g $\cdot m^{-2} \cdot yr^{-1}$ are shown.

```
Input location (longitude,latitude [degrees]): 20 47
Contributions to total sulfur deposition at (20.0,47.0):

    -------------------------------------------
    |  Country     |Deposition|   %    | sum % |
    |--------------|----------|--------|-------|
    |Hungary       |   2.595  | 49.35  | 49.35 |
    |Yugoslavia    |   0.568  | 10.79  | 60.15 |
    |Czechoslov.   |   0.516  |  9.82  | 69.97 |
    |Romania       |   0.425  |  8.07  | 78.04 |
    |Poland        |   0.289  |  5.49  | 83.53 |
    |German D.R.   |   0.206  |  3.91  | 87.45 |
    |Italy         |   0.174  |  3.31  | 90.75 |
    |BACKGROUND    |   0.151  |  2.87  | 93.62 |
    |F.R. Germany  |   0.101  |  1.92  | 95.54 |
    -------------------------------------------
```

Figure 4-6. Computed sources of sulfur deposition in mid-Hungary in the year 2010.

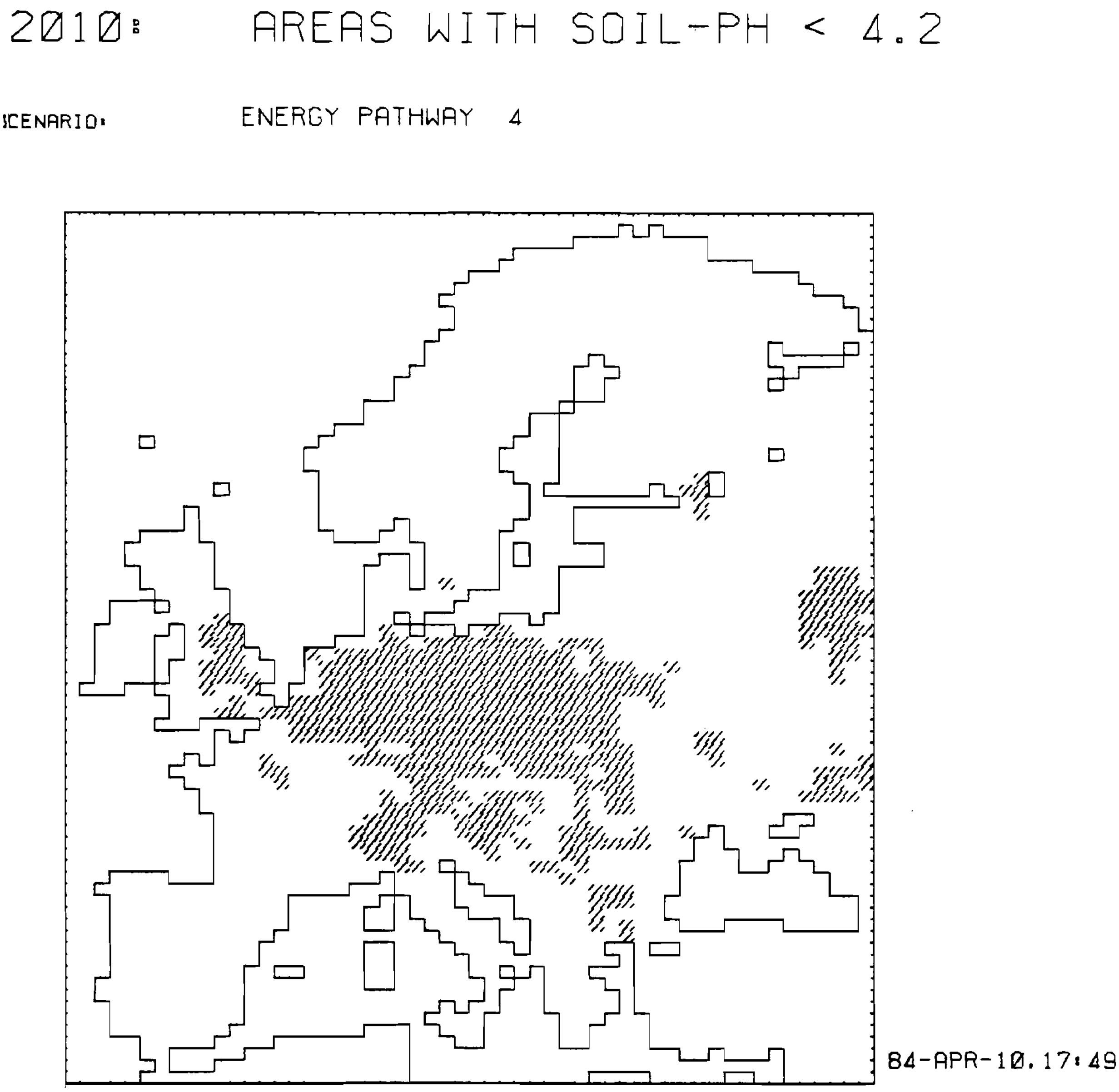

Figure 4-7. Area of forest soil with pH < 4.2, computed in example 1.

EXAMPLE 2 Comparing the Consequences of Two Different Energy Pathways

In this example, we introduce the procedure for comparing two different *energy pathways*. In brief, the user begins by selecting two, rather than a single, energy pathways. He/she can then compare -- (1) the energy data base; (2) sulfur emissions; (3) sulfur deposition; (4) forest soil pH.

In this example, we assume that the model user has selected the highest and lowest energy pathways, numbers 1 and 4. The user can then examine detailed tabulations of these data bases in the same format as Example 1. The user can also inspect a graphical comparison of the two energy pathways for any country of group of countries as noted in Figure 4-8.

As a next step, the user can look at a detailed tabulation of sulfur emissions as in *Example 1*. Alternatively, the model can produce the graphical comparison shown in Figure 4-9.

The user now selects an impact indicator as in the first example. To obtain a map of sulfur deposition, he/she once again specifies country (or group of countries), a sulfur deposition isoline, and year. The model then provides a map of sulfur deposition which compares the two energy pathways (Figure 4-10).

The model user follows the same procedure for examining forest soil pH as in Example 1. Once the user provides the needed information , the model presents a map comparing areas with forest soil pH less than 4.2 for the two energy pathways (Figure 4-11).

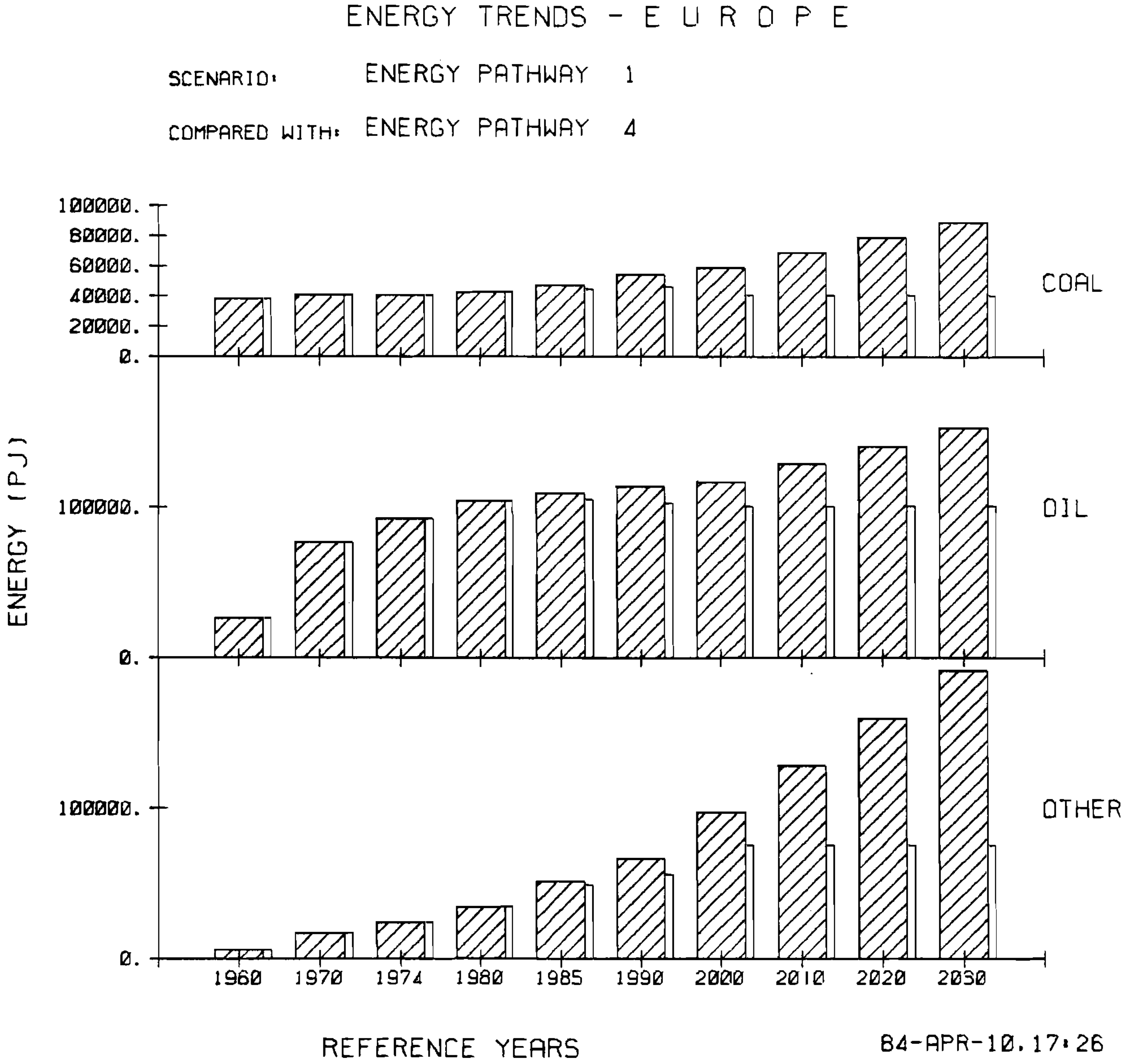

Figure 4-8. Comparison of energy use in example 2.

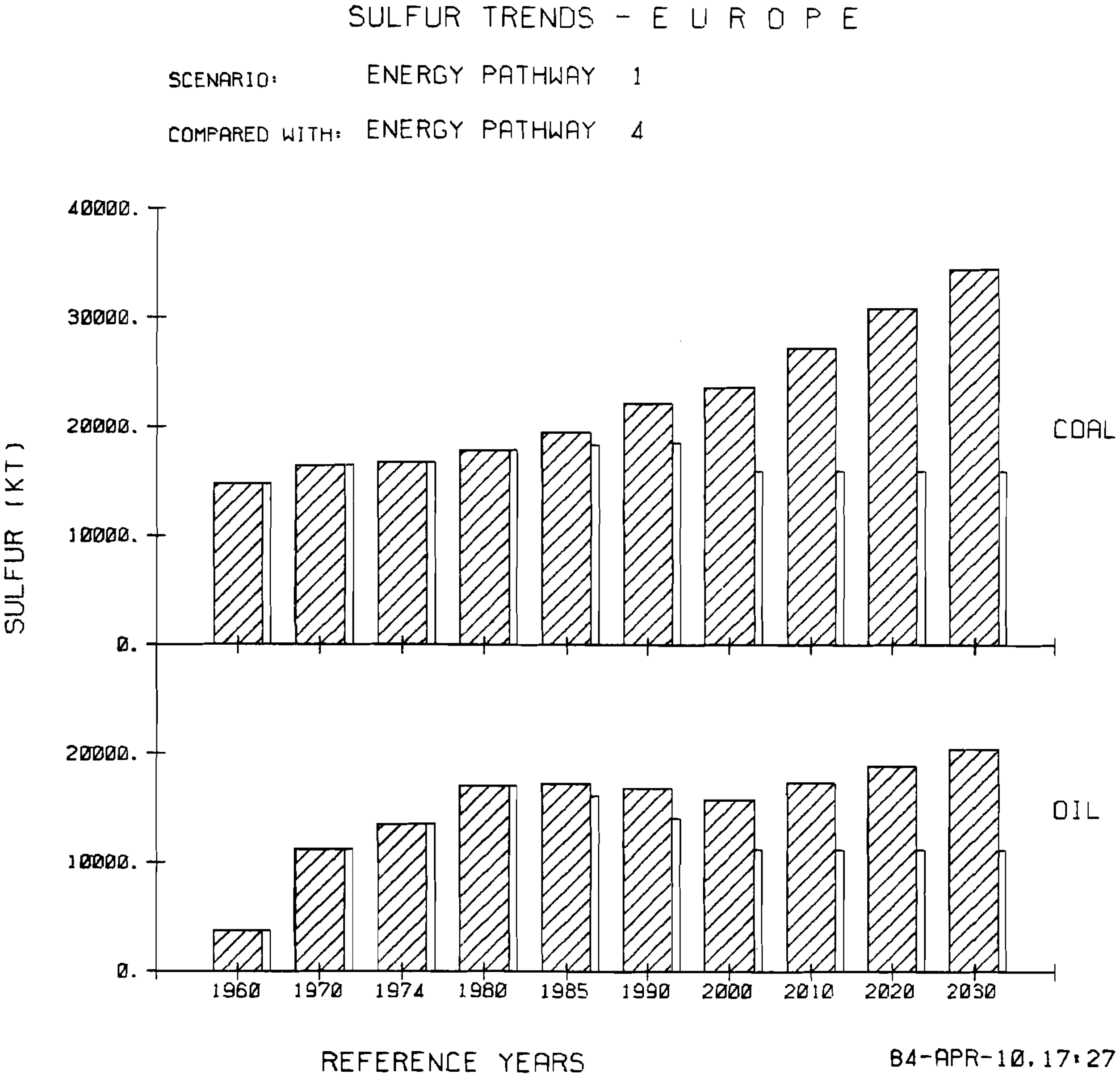

Figure 4-9. Comparison of computed sulfur emissions in example 2.

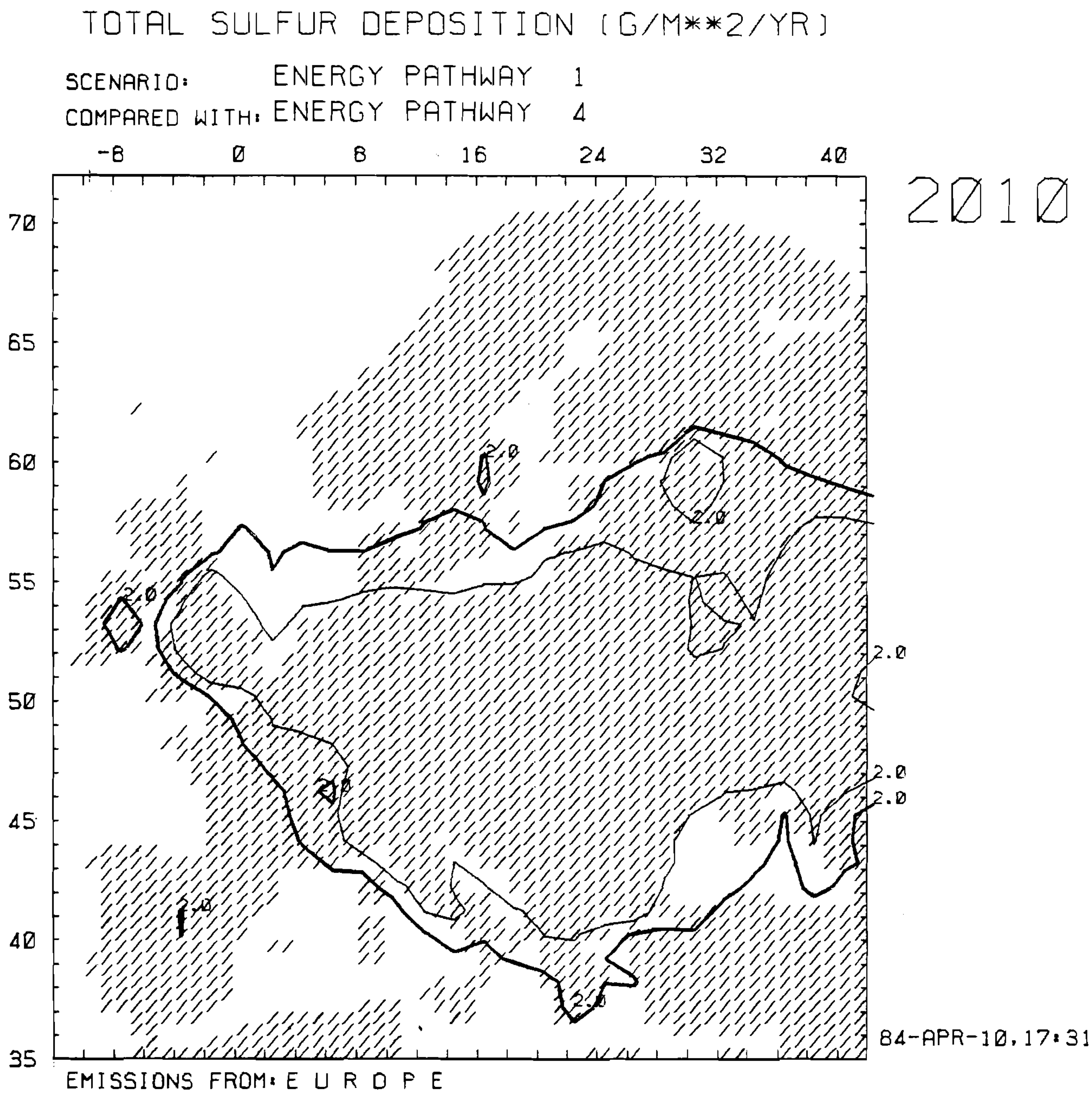

Figure 4-10. Comparison of computed sulfur deposition in example 2. The isoline of 2.0 g $\cdot$ m^{-2} $\cdot$ yr^{-1} is shown.

2010: AREAS WITH SOIL-PH < 4.2

SCENARIO: ENERGY PATHWAY 1

COMPARED WITH: ENERGY PATHWAY 4

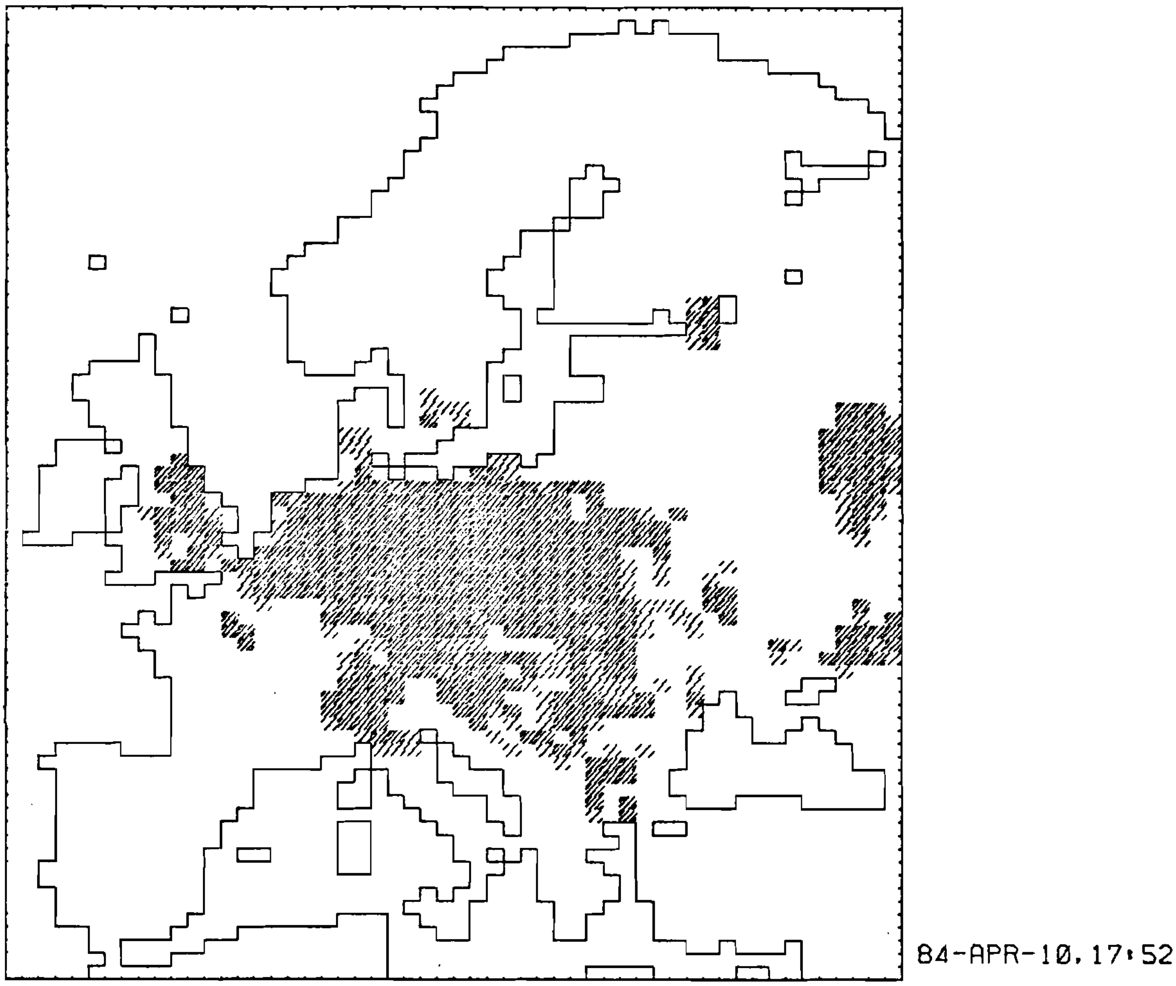

Figure 4-11. Comparison of computed forest soil pH in example 2.

EXAMPLE 3 Examining the Consequences of a Pollution Control Policy

We now illustrate how the model is used to evaluate different policies for controlling acid rain in Europe. In this example the user specifies a pollution control strategy and compares it with a case of 'no action'.

First we assume that for economic or other reasons, all nations of Europe follow energy pathway No. 4. Now we wish to compare two scenarios. One scenario calls for major pollution control activities and the other no pollution control*.

The pollution control scenario includes:

(1) 30% removal of sulfur in the domestic coal sector through coal cleaning and 60% removal of sulfur in the domestic oil sector by oil desulfurization..

(2) Phasing in of flue gas control devices in the power plant and industry sectors for coal and oil. We phase in these devices as follows:

Year	Fraction of sulfur removed**
1990	0.4
2000	0.6
2010	0.8
2020	0.8
2030	0.8

---

*Recall that a *scenario*, as defined in Chapter 2 of this paper is a ***consistent set of energy pathway, sulfur emissions, sulfur deposition and environmental impact***.

**This assumes that 50% of all power plants and industrial boilers in 1990 will have flue gas control devices which have an 80% sulfur removal efficiency (0.5 x 0.8 = 0.4). These devices will be applied to 75% of all plants and boilers in the year 2000 (0.75 x 0.8 = 0.6) and all plants after the year 2010 (1.0 x 0.8 = 0.8).

The complete procedure for developing this scenario interactively with the computer is presented in Appendix A. Figures 4-12, 4-13 and 4-14 summarize the differences between the two scenarios for the year 2010.

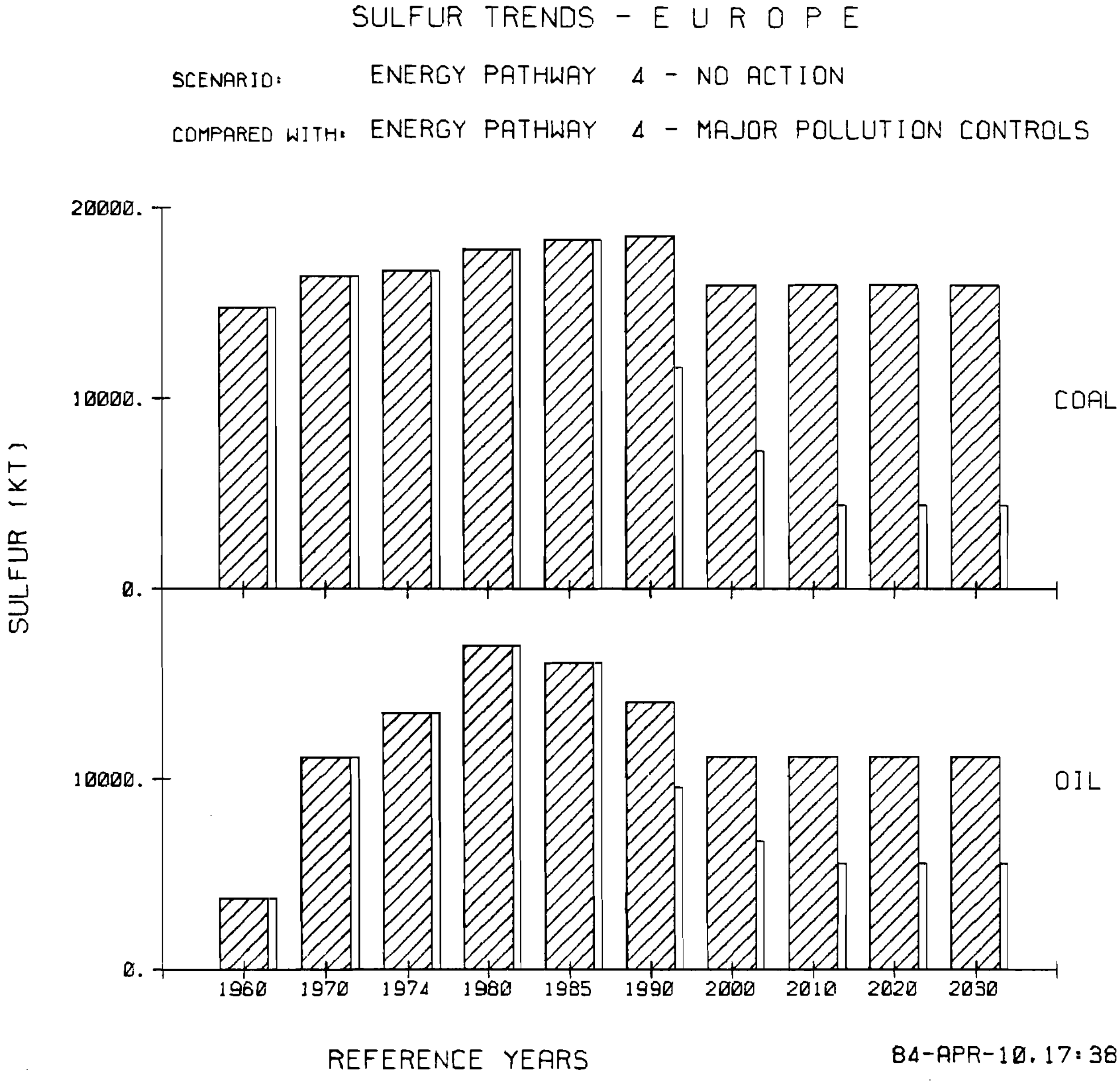

Figure 4-12. Comparison of computed sulfur emissions in example 3.

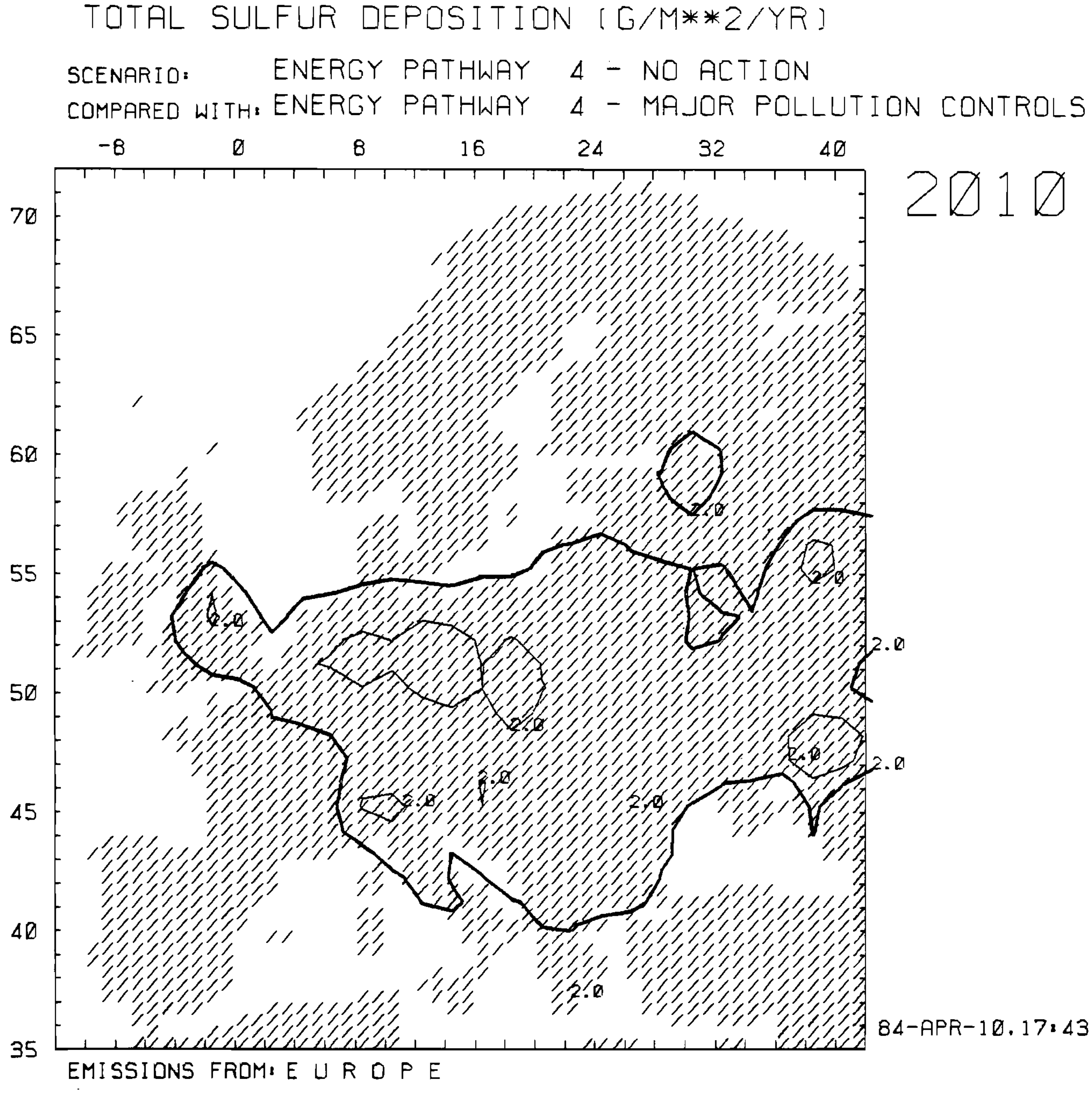

Figure 4-13. Comparison of computed sulfur deposition in example 3.

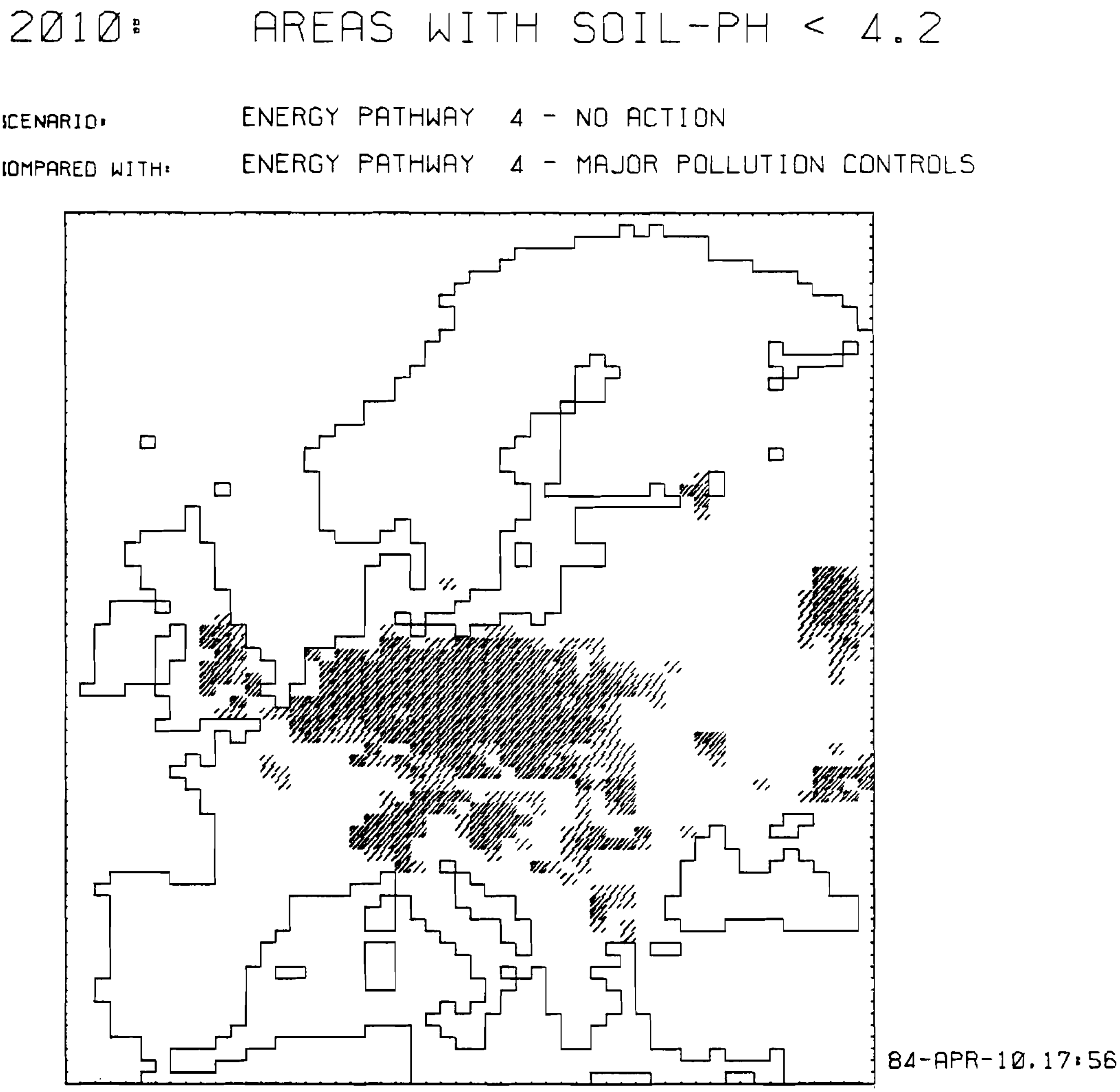

Figure 4-14. Comparison of computed forest soil pH in example 3.

CHAPTER FIVE

ONGOING PROJECT DEVELOPMENT

The work presented in this paper represents the initial steps in a much more extensive analysis of acid rain in Europe. This will include focusing on pollutants other than sulfur, for example NO_x, and possibly photoxidants, heavy metals and others. In the future we will also examine ***direct forest impact**** in addition to forest soil acidification. One of our next major steps will be to evaluate the impact of acid deposition on surface waters, especially lakes. Other possible impact areas to be incorporated in the model include materials' damage and acidification of groundwater. More specifically, our upcoming activities include:

(1) Testing and improvement of the three submodels presented in this paper.

(2) Evaluation of uncertainty of the existing model.

(3) Improvement of the interactive input and graphical output of the model.

(4) Addition of new submodels including (a) surface water impact; (b) direct forest impact; and perhaps (c) agriculture, (d) materials, and (e) groundwater.

---

* ***Direct forest impact*** refers to the effect of high ambient air pollutant concentrations on photosynthesis in a forest.

New submodels will also be included to account for NO_x emissions and deposition.

We will explore other ways to use the model other than through scenario analysis. This may include an extension of the model to allow model users to investigate the optimum policy for a particular cost or environmental objective. The model will also be used to assist in an analysis of costs and benefits of control strategies for acid rain in Europe.

We will of course, continue to introduce the model to decision makers and scientists for their comments and to encourage their use of the model. The first review meeting of this type, held in November 1983, yielded valuable comments from the participants which have been incorporated into our plans for further model development.

APPENDIX A

A SAMPLE INTERACTIVE SESSION

The following appendix presents a typical computer session in which a model user provides data needed to create a scenario. During this particular session the user creates the pollution control scenario described in Example 3 of Chapter 4.

The answers of the model user to the questions posed by the computer are indicated by a box: ☐

```
                    P L E A S E   N O T E :

             Due to the provisional nature of this model,
             please interpret model outputs cautiously.



Hit RETURN to continue:

The following scenarios are in the data base:

       1 ... ECE-Trends continued, linear extrapolation
       2 ... ECE-Trends continued, leveling off
       3 ... ECE-Conservation, linear extrapolation
       4 ... ECE-Conservation, leveling off




      You can now:

      a ... look at one of these scenarios
      b ... create a new scenario (starting from an old one)

Your option ('q' to quit): b
Which scenario?: 4

Input name of new scenario (max.50 char's):

>ENERGY PATHWAY #4 - Major Pollution Controls
A 'policy' consists in applying one (or more) of the following actions:


       1 ... sulfur removal by fuel cleaning

       2 ... sulfur removal by pollution control (devices)

       3 ... introduction of low sulfur power plants

       4 ... use of low sulfur fuel


Your choice: 2
```

```
In which country (-ies) do you want to apply this policy?:

        1 ... Albania           10 ... German D.R.        19 ... Portugal
        2 ... Austria           11 ... Greece             20 ... Romania
        3 ... Belgium           12 ... Hungary            21 ... Spain
        4 ... Bulgaria          13 ... Ireland            22 ... Sweden
        5 ... Czechoslov.       14 ... Italy              23 ... Switzerland
        6 ... Denmark           15 ... Luxembourg         24 ... Turkey
        7 ... Finland           16 ... Netherlands        25 ... United King.
        8 ... France            17 ... Norway             26 ... USSR
        9 ... F.R. Germany      18 ... Poland             27 ... Yugoslavia

       28 ... countries with market economy (2,3,6-9,11,13-17,19,21-25)
       29 ... countries with centrally planned economy (1,4,5,10,12,18,20,26,27)
       30 ... nordic countries (6,7,17,22)
       31 ... E U R O P E

Your choice: 31

When should your policy become operational?:

     1980 - 1985 - 1990 - 2000 - 2010 - 2020 - 2030

Input one of the above starting years: 1990

There are two options for a 'pollution control (device)' policy:

     1 ... pollution control devices on all NEW plants after 1990
           in industry and/or power plant sector

     2 ... user prescribed removal efficiency in reference years

Your option: 2

For which of the following COAL sectors do you want to change 'alpha'?:

           2 ... conv.
           3 ... PPcnv
           4 ... PPlow
           5 ... Dom.
           6 ... Ind.

           7 ... all COAL sectors

Your choice: 3 6
Input new 'alpha' (0<=alpha<=1):

for 1990: 0.4
for 2000: 0.6
for 2010: 0.8
for 2020: 0.8
for 2030: 0.8
```

```
For which of the following OIL sectors do you want to change 'alpha'?:

          2 ... conv.
          3 ... PPcnv
          4 ... PPlow
          5 ... Dom.
          6 ... Ind.
          7 ... Tran.
          8 ... Feed.

          9 ... all OIL sectors

Your choice: 3 6
Input new 'alpha' (0<=alpha<=1):

for 1990: 0.4
for 2000: 0.6
for 2010: 0.8
for 2020: 0.8
for 2030: 0.8

Do you want to apply another policy? [y/n]: y
A 'policy' consists in applying one (or more) of the following actions:




       1 ... sulfur removal by fuel cleaning

       2 ... sulfur removal by pollution control (devices)

       3 ... introduction of low sulfur power plants

       4 ... use of low sulfur fuel


Your choice: 1


In which country (-ies) do you want to apply this policy?:

       1 ... Albania          10 ... German D.R.       19 ... Portugal
       2 ... Austria          11 ... Greece            20 ... Romania
       3 ... Belgium          12 ... Hungary           21 ... Spain
       4 ... Bulgaria         13 ... Ireland           22 ... Sweden
       5 ... Czechoslov.      14 ... Italy             23 ... Switzerland
       6 ... Denmark          15 ... Luxembourg        24 ... Turkey
       7 ... Finland          16 ... Netherlands       25 ... United King.
       8 ... France           17 ... Norway            26 ... USSR
       9 ... F.R. Germany     18 ... Poland            27 ... Yugoslavia

      28 ... countries with market economy (2,3,6-9,11,13-17,19,21-25)
      29 ... countries with centrally planned economy (1,4,5,10,12,18,20,26,27)
      30 ... nordic countries (6,7,17,22)
      31 ... E U R O P E

Your choice: 31
```

```
When should your policy become operational?:

     1980 - 1985 - 1990 - 2000 - 2010 - 2020 - 2030

Input one of the above starting years: 1990

For which of the following COAL sectors do you want to change 'clean'?:

           3 ... PPcnv
           4 ... PPlow
           5 ... Dom.
           6 ... Ind.

           7 ... all COAL sectors

Your choice: 5
Input new 'clean' (0<=clean<=1):

for 1990: 0.3
for 2000: 0.3
for 2010: 0.3
for 2020: 03\3/.3
for 2030: 0.3

For which of the following OIL sectors do you want to change 'clean'?:

           3 ... PPcnv
           4 ... PPlow
           5 ... Dom.
           6 ... Ind.
           7 ... Tran.



           8 ... Feed.

           9 ... all OIL sectors

Your choice: 5 7
Input new 'clean' (0<=clean<=1):

for 1990: 0.6
for 2000: 0.6
for 2010: 0.6
for 2020: 0.6
for 2030: 0.6
```

```
Do you want to apply another policy? [y/n]:n

Do you want to look at this scenario? [y/n]:y
You can display the following data (parameters):

          a ... energy per fuel per process
          b ... sulfur content by weight
          c ... fraction brown coal of total coal
          d ... cleaning efficiency
          e ... sulfur removal efficiency
          f ... total sulfur emitted

Your option:e

for the following countries:

      1 ... Albania          10 ... German D.R.      19 ... Portugal
      2 ... Austria          11 ... Greece           20 ... Romania
      3 ... Belgium          12 ... Hungary          21 ... Spain
      4 ... Bulgaria         13 ... Ireland          22 ... Sweden
      5 ... Czechoslov.      14 ... Italy            23 ... Switzerland
      6 ... Denmark          15 ... Luxembourg       24 ... Turkey
      7 ... Finland          16 ... Netherlands      25 ... United King.
      8 ... France           17 ... Norway           26 ... USSR
      9 ... F.R. Germany     18 ... Poland           27 ... Yugoslavia

     28 ... countries with market economy (2,3,6-9,11,13-17,19,21-25)
     29 ... countries with centrally planned economy (1,4,5,10,12,18,20,26,27)
     30 ... nordic countries (6,7,17,22)
     31 ... E U R O P E

Your choice:11
Fraction of sulfur removed by pollution control in Greece
------------------------------------------------------------------------------
|    |             coal              |                  oil                  |
|----|-------------------------------|---------------------------------------|
|    |conv.|PPcnv|PPlow|Dom. |Ind.  |conv.|PPcnv|PPlow|Dom. |Ind. |Tran.|Feed.|
|----|-----|-----|-----|-----|------|-----|-----|-----|-----|-----|-----|-----|
|1960| 0.  | 0.  | 0.  | 0.  | 0.   | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  |
|1970| 0.  | 0.  | 0.  | 0.  | 0.   | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  |
|1974| 0.  | 0.  | 0.  | 0.  | 0.   | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  |
|1980| 0.  | 0.  | 0.  | 0.  | 0.   | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  |
|1985| 0.  | 0.  | 0.  | 0.  | 0.   | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  |
|1990| 0.  | 0.40| 0.  | 0.  | 0.40| 0.  | 0.40| 0.  | 0.  | 0.40| 0.  | 0.  |
|2000| 0.  | 0.60| 0.  | 0.  | 0.60| 0.  | 0.60| 0.  | 0.  | 0.60| 0.  | 0.  |
|2010| 0.  | 0.80| 0.  | 0.  | 0.80| 0.  | 0.80| 0.  | 0.  | 0.80| 0.  | 0.  |
|2020| 0.  | 0.80| 0.  | 0.  | 0.80| 0.  | 0.80| 0.  | 0.  | 0.80| 0.  | 0.  |
|2030| 0.  | 0.80| 0.  | 0.  | 0.80| 0.  | 0.80| 0.  | 0.  | 0.80| 0.  | 0.  |
------------------------------------------------------------------------------
```

```
Do you want to have another display? [y/n]: y
You can display the following data (parameters):




          a ... energy per fuel per process
          b ... sulfur content by weight
          c ... fraction brown coal of total coal
          d ... cleaning efficiency
          e ... sulfur removal efficiency
          f ... total sulfur emitted

Your option: d

for the following countries:

       1 ... Albania           10 ... German D.R.        19 ... Portugal
       2 ... Austria           11 ... Greece             20 ... Romania
       3 ... Belgium           12 ... Hungary            21 ... Spain
       4 ... Bulgaria          13 ... Ireland            22 ... Sweden
       5 ... Czechoslov.       14 ... Italy              23 ... Switzerland
       6 ... Denmark           15 ... Luxembourg         24 ... Turkey
       7 ... Finland           16 ... Netherlands        25 ... United King.
       8 ... France            17 ... Norway             26 ... USSR
       9 ... F.R. Germany      18 ... Poland             27 ... Yugoslavia

      28 ... countries with market economy (2,3,6-9,11,13-17,19,21-25)
      29 ... countries with centrally planned economy (1,4,5,10,12,18,20,26,27)
      30 ... nordic countries (6,7,17,22)
      31 ... E U R O P E

Your choice: 2
Fraction of sulfur removed by fuel cleaning in Austria
-------------------------------------------------------------------------
|    |          coal             |                  oil                  |
|----|---------------------------|---------------------------------------|
|    |PPcnv|PPlow|Dom. |Ind. |PPcnv|PPlow|Dom. |Ind. |Tran.|Feed.|
|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|1960| 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  |
|1970| 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  |
|1974| 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  |
|1980| 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  |
|1985| 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  | 0.  |
|1990| 0.  | 0.  | 0.30| 0.  | 0.  | 0.  | 0.60| 0.  | 0.60| 0.  |
|2000| 0.  | 0.  | 0.30| 0.  | 0.  | 0.  | 0.60| 0.  | 0.60| 0.  |
|2010| 0.  | 0.  | 0.30| 0.  | 0.  | 0.  | 0.60| 0.  | 0.60| 0.  |
|2020| 0.  | 0.  | 0.30| 0.  | 0.  | 0.  | 0.60| 0.  | 0.60| 0.  |
|2030| 0.  | 0.  | 0.30| 0.  | 0.  | 0.  | 0.60| 0.  | 0.60| 0.  |
-------------------------------------------------------------------------
```

```
Do you want to have another display? [y/n]: n

Do you want to save this scenario in the database? [y/n]:

The following scenarios are in the data base:

       1 ... ECE-Trends continued, linear extrapolation
       2 ... ECE-Trends continued, leveling off
       3 ... ECE-Conservation, linear extrapolation
       4 ... ECE-Conservation, leveling off
       5 ... ECE-Scenario 4 + major controls



      You can now:

      a ... look at one of these scenarios
      b ... create a new scenario (starting from an old one)

Your option ('q' to quit): q
```

REFERENCES

Alcamo, J., and M. Posch. 1984. A Model for estimating sulfur emissions and sulfur control in Europe. (Forthcoming IIASA Working Paper).

Economic Commission for Europe (ECE). 1983. An efficient energy future. Butterworths, London. 259 pp.

Eliassen, A. 1978. The OECD study of long-range transport of air pollutants: Long-range transport modeling. Atmospheric Environment. 12: 479-487.

Eliassen, A. 1980. A Review of long-range transport modeling. Journal of Applied Meteorology. 19(3):231-240.

Eliassen, A., and J. Saltbones. 1975. Decay and transformation rates for SO_2, as estimated from emission data, trajectories and measured air concentrations. Atmospheric Environment. 9:425-429.

Eliassen, A., and J. Saltbones. 1983. Modelling of long-range transport of sulphur over Europe: A two-year model run and some model experiments. Atmospheric Environment. 17(8): 1457-1473.

Fisher, B.E.A. 1984. Long-range transport of air pollutants and some thoughts on the state of modeling. Atmospheric Environment. 18(3): 553-562.

Highton, N.H., and M.J. Chadwick. 1982. The effects of changing patterns of energy use on sulfur emissions and deposition in Europe. Ambio. 11(6): 324-329.

Kauppi, P., M. Posch, E. Matzner, L. Kauppi and J. Kämäri. 1984. A Model for predicting the acidification of forest soils: application to acid deposition in Europe. (Forthcoming IIASA Research Report).

Lamb, R.G. 1983. Regional scale (1000 km) model of photochemical pollution - 1. theoretical formulation. EPA Report EPA-600/3-83-3035.

Lamb, R.G. 1984. Air pollution models as descriptors of cause-effect relationships. Atmospheric Environment. 18(3): 591-606.

Organization for Economic Cooperation and Development. 1981. Costs and benefits of sulfur oxide control. OECD. 164 pp..

Ottar, B. 1978. An assessment of the OECD study on long-range transport of air pollutants (LRTAP). Atmospheric Environment. 12: 445-454.

Rodhe, H. 1978. Budgets and turnover times of atmospheric sulfur compounds. Atmospheric Environment. 12: 671-680.

Semb, A. 1978. Sulfur emissions in Europe. Atmospheric Environment. 12: 455-460.