National Society for Clean Air and Environmental Protection

Transboundary Air Pollution: Feasibility Study of Global Integrated Assessment

First Report
A Review of Technical Issues and Capabilities
In the Application of Integrated Assessment
At Regional and Global Levels

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Introduction

1. This report reviews the current state of understanding in key areas relevant to the feasibility of global integrated assessment of transboundary air pollution. It focuses primarily on scientific issues and data availability, with policy and institutional implications being addressed more fully in a separate review.

2. This document is essentially a background paper and discussion document reflecting the considerations reviewed in the first half of a year-long study funded by the UK Department of the Environment, Transport and the Regions. It aims to:

   - provide background on progress in the application of integrated assessment, and other analogous techniques, to transboundary air pollution processes;
   - provide a basis for identifying and assessing, in the next stage of the project, the key issues which would arise from moving from the regional level to hemispherical or global levels;
   - identify current uncertainties and constraints which might be relevant to wider applications as well as any new ones which might be expected to arise.

3. The report is in three sections:

   - A short overview of where integrated assessment has now reached.

   - A fuller review of the state of play in the various inputs to assessment models:
     i. Emissions
     ii Transport and deposition
     iii Eco-system sensitivity and effects
     iv Abatement methods and costs

     Each section looks separately at regional studies and data, and (so far as available) at emerging work at global level. At this stage, however, each section is rather a preliminary attempt to scope the field and identify the key material rather than a definitive assessment.

   - A review of current uncertainties, although at this stage in no order of scale or importance.

4. The report is complemented by a separate paper which provides background assessments of environmental issues and data at regional level; a preliminary review of the prospects for developing global databases, and a separate bibliography.

I. Integrated Assessment Modelling: Where Are We?

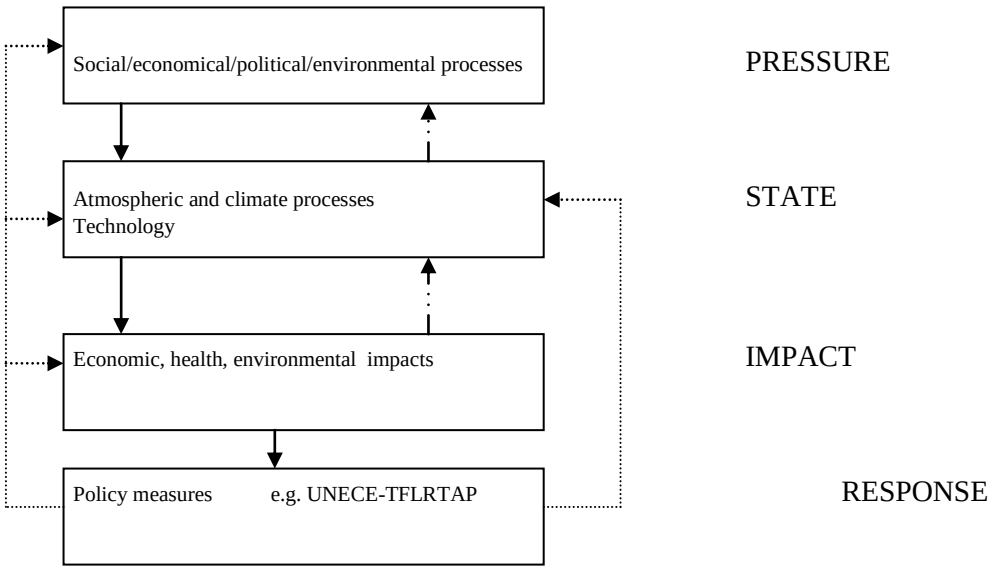
1. ORIGINS AND CONTEXT

The overriding goal of integrated assessment is to link science and policy by providing relevant and easy-to-understand information based on sound scientific knowledge and observations. While there are many definitions of integrated assessment, all have three elements in common: multi- or interdisciplinarity, structuring of knowledge, and decision-support. Using these common elements, integrated assessment can be defined (Rotmans, 1998) as: *a multi- or interdisciplinary process of structuring knowledge elements from various scientific disciplines in such a manner that all relevant aspects of a social problem are considered in their mutual coherence for the benefit of decision-making.*

Integrated assessment (IA) can be viewed as a puzzle where the real skill is in fitting the separate pieces together in a logical manner, which is more than the sum of its parts. IA is an iterative process, where integrated insights from the scientists are conveyed to the decision-makers, and experiences and insights from decision-makers are taken into account in the integrated analyses.

The term "integrated assessment" was first used in the early 1970s, mainly in the United States and Europe. The new feature then was the use of the so-called integrated design methods: conceptual models and computer simulation models. During the 1980s and 90s many integrated environmental models were developed in Europe and the United States. While in Europe the ecological consequences of human perturbations were the primary concern, in the United States it was the economic impacts of human actions. IA partly overlaps with existing research areas such as Technology Assessment, Risk Analysis and Policy Analysis.

An example of IA would, therefore, be an interdisciplinary and iterative process of structuring knowledge elements from various scientific disciplines, which considers all relevant aspects of the problem and which is to be used for the benefit of decision-making. It should follow the PSIR (pressure-state-impact-response) diagram:



Although active participation is not a prerequisite, an increasing number of those involved in IA are convinced of the need to include stakeholders in the IA-process. The reality, however, is that there is almost no interaction between the two groups of researchers operating within the field of IA: while the analysts have a practical approach, developing and applying integrated tools such as models, indicators or scenarios, social scientists hold the reflexive point of view that IA is a participatory process. There is also a gap between the decision-makers and the scientists. As the use of IA widens it will be important that these gaps are bridged.

The complex, intuitive, and value-laden process of IA cannot be approached from only one perspective. In general, two types of IA method can be distinguished - analytical and participatory. Analytical methods are often associated with natural sciences and participatory methods with social sciences. The group of analytical methods is reasonably well defined and basically includes model analysis, scenario analysis and risk analysis. Their commonality is that they provide analytical frameworks for representing and structuring scientific knowledge in an integrated manner. Examples of analytical methods are the models and the scenarios. The group of participatory methods, however, involves a variety of methods, from expert panels, to role-play, policy exercises and focus groups. All these methods aim to involve non-scientists as stakeholders in the process, where the assessment effort is driven by stakeholder-scientist interactions.

The PSIR framework has been developed to give at least some guidance on, and insight into, information analysis, data needs and interlinkages. Starting with the broad definition of issues to be assessed (e.g. climate change), information and data requirements can be obtained, eventually down to the level of time series for country energy use, meteorological station data, sub-national population growth, regional trade statistics, gridded land cover patterns etc.

2. MAIN INTEGRATED ASSESSMENT MODELS USED IN INTERNATIONAL NEGOTIATIONS

Studies in the 1970s confirmed that pollutants often travelled long distances before falling to earth. In 1979 the Convention on Long-range Transboundary Air Pollution (CLRTAP) was signed by 35 countries, including all states in Europe, the USA, and Canada. The Convention, which was negotiated through the UN Economic Commission for Europe, has become a framework for subsequent efforts to limit air pollution.

Integrated assessment models have been used in recent years in international negotiations on acid rain. The purpose of these models is to provide negotiators with a full picture of the problems associated with their causes, from energy systems and emissions through to the ultimate impact on natural and manmade systems. The model user can analyse the regional and national implications of various scenarios, including options for energy use, control strategies, and mitigation policies.

2.1 RAINS

a. Acidification

In 1985, 20 parties to the Convention signed a protocol stating that by 1993 they would reduce annual emissions of sulphur dioxide, the main source of acidification, by at least 30 percent, compared to 1980 levels. This across-the-board emissions reduction plan ignored the fact that some ecosystems are very sensitive to acidification while others are not. In addition, this plan did not take into account that some measures can be implemented more cheaply and quicker others.

The 'Regional Air Pollution INformation and Simulation' (RAINS)-model has been developed by the International Institute for Applied System Analysis, IIASA, as a tool to address these issues (Alcamo et al., 1990). It consists of an integrated assessment model describing cost-effective strategies to reduce acid deposition in Europe. RAINS was adopted by all parties to the international negotiations - the first time that a single computer model has ever been accepted as a key tool in the negotiations.

The RAINS model describes the pathways of emissions of sulphur dioxide, nitrogen oxides and ammonia and explores their impacts on acidification and eutrophication (Amann et al., 1996). The various sub-models are organised into three modules: the emission-cost module (EMCO), the acid deposition and ecosystems impact module (DEP), and the optimisation module (OPT).

- **EMCO** estimates current and future levels of emissions of SO_2, NO_x and ammonia. These estimates are based on national statistics and projections of economic activity, energy consumption levels, fuel characteristics, agricultural activities, etc, taking into account implemented and possible emission control measures. The time horizon extends from the year 1990 up to the year 2010. EMCO also estimates costs for the reduction of emissions. RAINS also provides "national cost curves" which rank abatement measures according to their cost-effectiveness. To develop an integrated abatement strategy the user can apply specific control policies (consistent sets of control measures) to selected emission sources in individual countries.

- **DEP** provides estimates of acid deposition loads throughout the region under study as a function of changing emissions and to compare them with maps of environmental sensitivities (the "critical load maps"). The emission data is used as input to DEP. Acid deposition fields are estimated using linear transfer matrices for the various substances. These transfer matrices are constructed from the results of the EMEP long-range atmospheric transport model, providing information on the dispersion of pollutants from the various sources (countries) to the land-based grid cells of the modelling domain.

- **OPT** identifies, for a given set of regional target deposition levels (which can be derived, e.g. from critical loads), the cost-minimal allocation of measures to reduce emissions. This optimisation takes into account that some emission sources are linked via the atmosphere to sensitive receptors more strongly than others (as reflected in the atmospheric transfer matrices), and that some sources are cheaper to control than others (as captured by the cost curves).

b. Eutrophication

During the renegotiation of the sulphur protocol in the early 1990s, negotiators became aware of the complexity of air pollution chains and the power of integrated assessment tools in helping to find more effective, less costly solutions. The inefficiency of single-pollutant agreements became clear when they began to renegotiate the nitrogen oxides protocol.

The paths of NO_x through the environment, and its impact, are much more complex than those of sulphur. In the presence of sunlight, NO_x combines with VOCs and CO to form O_3. This highlights the need to negotiate controls on NO_x and VOCs simultaneously. Moreover NO_x, like SO_2, is also an important source of acidification (responsible for about 20 percent in Europe, compared to 60 percent for sulphur and 20 percent for ammonia). However, unlike sulphur, nitrogen is also a basic plant nutrient. It can be taken up by plants, often to excess, creating the problem of over-fertilisation, or eutrophication. Nitrogen from ammonia (NH_3) can have the same impact.

This complexity makes it impossible to calculate a simple critical load value for a determined ecosystem. In reality, it is impossible to have just one fixed level due to the fact that, while the total amount of acid deposition is important, the ratio of sulphur to nitrogen can also be exrtremely important depending on the ecosystem. RAINS takes this into account by considering not just one number for total acid deposition, but pairs of numbers, with one value for sulphur deposition and one for nitrogen.

Going one step further, a logical approach to combatting acidification and eutrophication suggests that ammonia, the other key source of airborne nitrogen, should be included in the negotiations. This resulted in the current negotiations for measures to control the four main pollutants (SO_2, NH_3, NO_x, and VOCs) responsible for three major environmental problems: acidification, eutrophication, and ozone formation. This multi-pollutant, multi-effect approach offers clear environmental and financial advantages, but its complexity raises a host of problems. Scientists and decision-makers had to move from single objectives that could always fall back on one-dimensional questions to a huge number and variety of cross-linkages.

c. Ozone

Scientists found that background concentrations of ozone in Europe are at least twice as high as they were a century ago. This excessive ozone in the lower atmosphere (tropospheric ozone, as opposed to stratospheric, or high-altitude, ozone) damages crops, weakens trees, and harms human health, especially in people weakened by bronchitis, heart disease, emphysema, or asthma.

Tropospheric ozone is a secondary pollutant, which forms when nitrogen oxides, volatile organic compounds, and carbon monoxide mix in the presence of sunlight. Nitrogen oxide and carbon monoxide arise mainly from burning fossil fuels; the volatile organics come from solvents, paints, evaporating fuels and other chemicals.

Areas with typically low nitrogen oxide concentrations need to try to reduce these concentrations even further in order to reduce ozone. However, in other areas with higher NO_x concentrations, reducing these levels could actually increase ozone pollution. If one also considers that NO_x is a factor in two other environmental problems - acid rain and eutrophication - the complexity becomes overwhelming. Integrated assessment tools should help in analysing all the possible combinations and trade-offs, weight them according to the user's criteria, and point to a reasonably balanced, cost-effective solution. An integrated assessment of ozone pollution must, therefore, take account of the entire chain of pollution, from the emission of each chemical precursor to its final impact on human health and the environment.

For years, it was considered almost impossible to include ozone in an integrated assessment model due to the complexity of its chemistry. Only a large and detailed research model (such as the one from the Norwegian Meteorological Institute in Oslo) with massive computing power could simulate it accurately. This was simply too big for an integrated assessment tool like RAINS.

Between 1994 and 1997, scientists at the International Institute for Applied System Analysis (IIASA), with the help of colleagues in Norway and Germany, succeeded in bringing ozone into the RAINS framework. The model has played a key role in efforts to develop new "second generation" strategies to control air pollution in Europe. Researchers at IIASA designed a set of 2000 scenarios that amounted to a list of possible combinations of ozone-forming chemicals and conditions. The scenarios were then calculated in Norway using parallel computing tools to create a large set of statistical data. IIASA then analysed this data statistically and found a single representative equation; given essentially the same input data, this one-equation model produces estimates of ozone formation within 1 or 2 percent of estimates made by its giant precursor in Norway; additionally, the model produces estimates quickly and can be run on a personal computer.

d. Fine airborne particles

The most recent European air pollution agreements and protocols, signed by the UNECE-CLRTAP, should greatly reduce problems of acid rain and ozone pollution. These agreements, however, overlook another pollution problem: the damage to human health caused by fine airborne particulate matter (PM). Airborne particulates arise mostly from the exhaust of cars, trucks, and power plants. So-called secondary particles are formed from

pollutant gases, including sulphur dioxide and nitrogen oxides. They cause respiratory and cardiovascular diseases and have been linked to increased rates of mortality.

IIASA has begun to assess systematically the current state of knowledge about the entire chain of particulate pollution, from emissions to impact on health. The aim is to develop a model of particulate pollution and to incorporate it into RAINS, linking it to tools for the study of sulphur dioxide, nitrogen oxides, ammonia, and volatile organic compounds. Such a model would make it possible to prioritise abatement measures for different environmental problems, and to identify those measures that contribute to the solution of several problems.

The initial implementation of the RAINS PM module on the internet enables free access to the input data and facilitates interaction with national experts. IIASA is aiming to implement it to allow users to develop their own emission inventories and projections in a fully interactive way and to examine the implications on PM emission control cost curves. Ultimately, IIASA aims to provide full access to the RAINS model via the Internet. The data, which has been implemented to date, was obtained from internationally available databases and literature sources. This is documented in Johansson et al., (2000) and most databases can be found on the IIASA website. Work is continuing in this respect.

2.2 ASAM

The aim of the second sulphur protocol (Oslo, 1994) under the CLRTAP, is to effect further reductions in SO_2 emissions across Europe. Three models were used in the development of this protocol (ApSimon et al., 1996) under the Task Force on Integrated Assessment Modelling (TFIAM): the RAINS model of IIASA (Alcamo et al., 1990), the Co-ordinated Abatement Strategy Model (CASM) of the Stockholm Environment Institute (SEI, 1991) and the Abatement Strategies Assessment Model (ASAM) of Imperial College (ApSimon et al, 1994). These models use source-receptor matrices derived from the EMEP-LADM model (which give a picture of the atmospheric transport between the source and different receptor areas across Europe) to estimate, among other things, scenarios that map the concentrations of secondary particulates for different years.

ASAM (ApSimon et al, 1994) has been prepared as a computer tool to assist in developing progressive reductions of acid deposition to achieve environmental goals, making full use of the EMEP results, using the same mapping system and source distribution. This is consistent with critical loads maps which have also been prepared on the same European grid, by estimating the proportions of each grid cell which lie in different classes of sensitivity to deposition of acidic species. Different critical load maps can be specified according to the level of protection.

As can be seen from the above, a policy of reducing the emissions which contribute to most of the deposition in the sensitive regions where critical loads are exceeded, will require less reduction overall in European emissions than a uniform percentage reduction, for the same environmental improvement (Derwent, 1988, 1990). However, the costs of emission control vary a great deal according to the type of emission and the technology implemented. Thus in each country there will be a range of sources and various possibilities to reduce emissions with different degrees of stringency. The costs per unit reduction in sulphur or nitrogen emissions characteristically increase sharply as percentage reductions become large.

The ratio of environmental benefit, in terms of approaching critical loads, to the cost of implementing the corresponding emission reduction is an important factor in policy development. ASAM has therefore been developed so it can derive sequential emission reductions which maximise the "environmental benefit : cost" ratios. The ranking techniques used have been named the Best Economic Environmental Pathway, BEEP. At each step a source is selected for reduction of emissions on the basis that it produces the best environmental benefit for the cost incurred. The environmental benefit is determined as an integral across the map area in terms of reduction of exceedances over critical loads or target loads. Flexible weighting functions can be introduced to emphasise the relative importance of different areas or constraints on expenditure in different countries. Thus a gradual reduction plan is derived by successively ranking the sources, for which the convergence towards the environmental goal can be charted against increasing expenditure or national or total percentage reductions in emissions. ASAM is a conceptually simple model which uses geographical distribution of emissions, source-receptor matrices derived by EMEP, critical load maps compiled by at the Dutch National Institute for Public Health and the Environment, RIVM, and information on emission control options and associated costs from IIASA.

ASAM derives emission abatement strategies, which are specifically aimed at reducing acidification, eutrophication and secondary particulate exposure (SO_2, NO_x and NH_3). A new version of ASAM, which will incorporate primary particulates in its modules, is currently being developed.

2.3 CASM

The Stockholm Environment Institute, SEI-York, has developed an integrated assessment model, the Co-ordinated Abatement Strategy Model (CASM); this links emissions of sulphur and nitrogen oxides with atmospheric transfer, a map of sensitivity to acidic deposition for Europe, and costs of abatement option application in each European country (Bailey, 1996 a,b; Cambridge, 1996).

CASM was developed to generate and evaluate abatement scenarios to support policy development. The model takes information describing atmospheric emissions and their long-range transport, costs of abatement and critical loads, and uses an optimisation procedure to generate cost-effective environmentally targeted strategies.

CASM is also being applied to air pollution from the transport sector. The project aims to examine how emissions of transboundary air pollution from the transport sector can be reduced in Europe through the application of different policy instruments. Initial investigations on sulphur also led to research on critical loads for nitrogen deposition and an on-going project determining the impact of troposphere ozone on crops and forests.

The CASM model is being used in a project called ‘Accounting and Accreditation of Activities Implemented Jointly’. This project investigates the Framework Convention on Climate Change and the Oslo Protocol (on sulphur emission reductions).

This EU-funded project involves both the SEI-York and the SEI-Tallinn office which is collecting data related to joint implementation projects in the Baltic Region for both climate

change and sulphur-related activities. SEI-York is analysing joint implementation projects and proposals under the sulphur protocol using case studies in parts of Europe. These activities will lead to sensitivity analysis and methodological guidelines for implementation.

2.4 RAINS-ASIA

Southeast Asia is on the verge of an acidification problem as widespread and severe as anything seen in North America or Europe. Spectacular economic growth has led to sharp increases in consumption of energy and consequently to sharp increases in emissions of sulphur dioxide. Moreover, local pollution problems are already severe: 12 of the 15 most polluted cities in the world (those with the highest levels of fine airborne particles) are in Asia. If nothing is done, widespread environmental and health problems are inevitable.

In 1992 the World Bank agreed to fund development of a variant of RAINS for Southeast Asia. The aim was to prepare a tool comparable to RAINS-Europe for Asia before the problem got out of hand, and to have it available for when there was the political will to negotiate agreements on air pollution. The project brought together a dozen research teams from Asia, Europe, and the USA. IIASA was responsible for developing the basic model, integrating material from other teams and assessing possible strategies to control acidification.

Rather than design a variant specifically for Asia, IIASA took the opportunity to redesign the model structure so that it can be applied to any world region. The European and Asian versions are essentially the same model with different input data.

When the project was being developed, the main problem was the limited data. In some cases, national averages were used for specific regions. In other cases, when data were completely unavailable at the country level, data from the RAINS-Europe model, representing typical values for these parameters in Europe, were used until more suitable Asian-specific data could be developed. Moreover, there were wide uncertainties in the emissions, in the deposition patterns, and in the meteorological data, etc, and assumptions had to be made. However, despite all these uncertainties the results obtained with RAINS-ASIA for sulphur deposition in South East Asia appear broadly similar to other modelling studies, such as the Asian-Pacific Integrated Model, AIM, of Morita et al (1995)

IIASA completed the first version of RAINS-Asia in 1994. Preliminary calculations using 1990 data indicated that acid deposition was already high enough to cause long-term damage in much of China, Indochina, and Japan. Future projections showed levels of acid deposition three times higher in some areas of China than the worst ever recorded in the infamous Black Triangle of Central Europe.

Everything suggests that RAINS could become a prominent tool for IA of air pollution in Southeast Asia, although further development is necessary. The initial versions deal only with sulphur dioxide. Truly comprehensive policy assessment would require, at a minimum, the addition of tools and data for nitrogen oxides and for fine airborne particles.

Work is underway to verify and improve various model elements. Meanwhile, researchers at IIASA and in Asia are using RAINS-Asia to analyse the potential for renewable energy to

solve some of Asia's pollution problems and to study large-scale pollution problems in East Asia.

2.5 WORK IN THE UNITED STATES

There have also been some integrated assessment projects in North America, such as the Mid-Atlantic Integrated Assessment (MAIA). This project, carried out under the auspices of the US EPA (Environment Protection Agency), is a research, monitoring, and assessment initiative. Its main goal is to develop high-quality scientific information on the condition of the natural resources of the Mid-Atlantic region of the eastern US. MAIA is an Interagency, multi-disciplinary program integrating and assessing research and monitoring information to provide answers to policy and management questions. It deals with ecological issues (e.g. acidification, eutrophication, climate change, etc), human health issues (such as asthma and other effects of ozone or particulates, etc) and socio-economic issues.

The US National Acid Precipitation Assessment Program, NAPAP, is another example of integrated assessment project. Since the 1980s, the research and periodic assessments conducted by NAPAP have helped to further understanding of the scientific processes and effects of acid deposition. Peer reviews, workshops, and annual reports culminated in the NAPAP 1990 Integrated Assessment Report. The monitoring and research conducted in the 1980s and the subsequent integrated assessment provided a significant part of the scientific knowledge base for Title IV of the 1990 Clean Air Act Amendments, known as the Acid Deposition Control Program. The purpose of Title IV is to reduce the adverse effects of acid deposition through reductions in annual emissions of its precursors, sulphur dioxide (SO_2) and nitrogen oxides (NO_x).

Subsequently, Congress authorised NAPAP to continue co-ordinating acid rain research and monitoring. In addition, Congress asked NAPAP to assess the costs and economic impacts of complying with the Acid Deposition Control Program as well as benefit analyses associated with the various human health and welfare effects, including reduced visibility, damage to materials and cultural resources. NAPAP also assesses effects on ecosystems as well as estimating the reductions in deposition rates needed to prevent adverse ecological effects.

Other current international research projects do not really come under the umbrella of integrated assessments, although they could be valuable starting points for extending integrated assessment to other regions.

II. Review of Key Areas

1. EMISSION TRENDS

1.1 CURRENT EMISSIONS

The quantification of pollutant emissions has largely been driven by international agreements. In recent years, several international agreements have had an enormous influence on the creation of emission inventories.

a. UNECE Region

a.1 a.1 Major pollutants (S, C and N compounds, photo-oxidants and VOCs)

The Convention on Long-Range Transboundary Air Pollution (CLRTAP) was adopted in Geneva in 1979. Reporting of emission data to the Executive Body of the Convention is required in order to fulfil obligations regarding strategies and policies in compliance with the implementation of Protocols under the Convention. EMEP is responsible for developing the emission database for the CLRTAP. It was also decided that efforts for harmonisation of the ECE data with other international inventories was necessary, in particular the CORINAIR work supervised by the European Environment Agency's (EEA) Topic Centre on Air Emissions (ETC-AE). Parties to the Convention are committed to submitting their official emission data and should use the EMEP/CORINAIR Atmospheric Emission Inventory Guidebook both as a reference book on good emission estimation practice and as a checklist to ensure that all relevant activities are considered and their emissions quantified. The second edition of the joint EMEP/CORINAIR Atmospheric Emission Inventory Guidebook (1999) has been prepared by expert panels of the UNECE/EMEP Task Force on Emission Inventories and is published by the European Environment Agency. Parties are required to submit annual national emissions of sulphur oxides (SO_2), nitrogen oxides (NO_x = NO and NO_2), ammonia (NH_3), non-methane volatile organic compounds (NMVOCs), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), heavy metals (priority metals: cadmium (Cd), mercury (Hg), lead (Pb)) and selected POPs using the 11 main source categories. Parties are also required to provide EMEP periodically with emission data within grid elements of 150km x 150km or 50km x 50km, as defined by EMEP and known as the EMEP grid.

The emission inventories held at the MSC-W are used for modelling purposes and need to be complete. Where no official information is available, estimates are taken from available open sources (e.g. CORINAIR, OECD, IIASA etc), or in some cases are made in collaboration with experts from the MSC-W and CCC. Annual totals for missing years are based on linear interpolation or extrapolation of the most recent official value. In the absence of any projection figures, however, the values used are those for 1990, since this year constitutes the basis for the estimation of national projection figures.

EMEP provides emissions maps for all the pollutants mentioned above for all the UNECE countries and has been the main source of data on emissions of pollutants for most of the studies done in Europe, such as those carried out with the RAINS-Europe model. For instance, some of the research projects carried out under the EUROTRAC programme have been using these and other detailed inventories from regional agencies as sources. GENEMIS involves the development of a unique set of emission data for regional chemical episodes. This is a much more specific inventory with high temporal and spatial distribution for the study of episodes.

a.2 a.2 Primary particulates

Countries in Europe are beginning to assemble emission inventories for primary particulates. At the current time, however, the only existing emission inventories in Europe are those prepared by The Netherlands Organisation for Applied Scientific Research, TNO, (Berdowski

et al., 1997b) and, more recently, the one compiled by IIASA (Johansson et al., 2000). Both inventories are full of uncertainties. RAINS is to include primary particulates in its structure, as are other models used by other research groups in Europe.

a.3 a.3 Heavy metals and POPs

EMEP has also developed a model for the calculation of concentrations and deposition of heavy metals and persistent organic pollutants (POPs) in Europe, for which emission inventories had first to be created. Heavy metals from natural emissions in Europe are not very well quantified, although some studies have been done to this respect (J. Nriagu, 1989). High volatility of mercury determines its continuous emission to the atmosphere from rocks and soils and recently the rates of mercury emissions from volcanic sources of Italy were quantified (Ferrara et al., 1999; Forlano, 2000). With respect to anthropogenic emissions, the EMEP model calculations were carried out on the basis of the official emission data; for the countries which have not submitted their official data, emissions were mainly estimated from J. Pacyna (1999) and from estimates obtained under the TNO/UBA project (Berdowski et al., 1997a).

The EMEP model for the study of POPs used expert estimates of selected POPs (PCB, B[a]P and g -HCH) emissions for several years made under the POPCYCLING-Baltic project (Pacyna et al., 1999). Since official emission data are not available for the whole simulation time period, nor for all European countries, model calculations were carried out on the basis of expert estimates. Between the basic years a linear interpolation of emissions was used.

The UN-ECE CLRTAP has agreed a protocol on persistent organic pollutants, and UNEP has also initiated negotiations on an international legally binding instrument for implementing international action on POPs. Under this global process, the twelve POPs being considered initially are PCBs, dioxins, furans, aldrin, dieldrin, DDT, endrin, chlordane, hexachlorobenzene, mirex, toxaphene and heptachlor.

b. North America

a.4 b.1 Major pollutants

The USEPA's National Air Emissions Inventory includes emissions from all States for all major pollutants. The Compilation of Air Pollutant Emission Factors, AP-42, is divided into two volumes. Volume I contains information on over 200 stationary source categories, including brief descriptions of processes used, potential sources of air emissions from the processes and in many cases common methods used to control these air emissions. Methodologies for estimating the quantity of air pollutant emissions are presented in the form of Emission Factors. Volume II contains information on emission factors from mobile sources. Potentially, these emission factors could also be extrapolated to other parts of the world, taking into account economic and social differences. NAPAP estimates that SO_2 emissions have been declining for the last twenty years, partly due to legislation and partly to a switch to low-sulphur fuels. On the other hand, NO_x emissions have remained more or less the same over the past years in the US.

The emission inventories in the US are largely developed, and cover major air pollutants such as sulphur oxides (SO_2), nitrogen oxides (NO_x = NO and NO_2), ammonia (NH_3), non-methane volatile organic compounds (NMVOCs), methane (CH_4), carbon monoxide (CO), carbon dioxide (CO_2), heavy metals (HM) and persistent organic pollutants (POPs)

In the US the study of fine particulate matter is more developed than in Europe, and emissions factors are included in AP-42. The emission inventories for primary particulate matter recently created for Europe, are largely based on the information in AP-42. However, it is necessary to bear in mind that many of their emission factors are very specific to the US (due, among other factors, to different climatic, technological and road conditions).

c. Asia

a.5 c.1 Major pollutants

The RAINS Asia work - as an example of an Integrated Assessment Study done outside the borders of Europe and the North America (where IA is more developed) - has been based on an emission inventory of acidifying pollutants in South East Asia. Emissions data for the different countries in the region were obtained from a number of independent studies, such as Akimoto et al., (1992, 1994) or Joshi et al., (1991). Where this was not possible, emission factors, taken from independent studies, such as Spiro et al. (1992), and from the USEPA, were used together with energy/fuel consumption data. The energy use by fuel type sector was obtained from IEA (1989); for other types of emissions such as emissions from shipping, the activity data was taken from UN databases and other similar documents.

d. Arctic

a.6 d.1 Heavy metals and POPs

In response to the United States commitment to serve as lead country for heavy metals under the Arctic Monitoring and Assessment Program (AMAP), the USEPA sponsored an international workshop on Heavy Metals in the Arctic. On air emissions, they concluded that anthropogenic sources and fluxes of mercury (Hg) and other heavy metals need to be more accurately listed. Emphasis also needs to be placed on measuring emission rates from natural sources. A significant contributor to the total budget of heavy metals in Arctic air comes from long range transport. This needs to be measured, particularly from sources in Russia and China, two of the largest producers of Hg emissions to air.

AMAP considers POPs to be an important contaminant in the Arctic, and further assessments of this issue are planned for the future. As part of this process, AMAP organised a workshop on POPs in the Arctic (AMAP, 1998) with particular reference to human health and environmental concerns. The main objectives of the workshop were to present recent results and new findings from scientific research, as well as to identify gaps in knowledge and to facilitate exchange of knowledge between individuals and groups working on environmental contamination by POPs and those working on the effects on human health of exposure to POPs. A number of interesting studies were presented on emissions of some POPS, such as that by Li et al. (2000) on global emissions.

e. Rest of world

a.7 e.1 Major pollutants

Other countries in other continents have their own emission inventories. Studies using the STOCHEM and other models (MOGUNTIA) have referred to independent studies in order to obtain their global maps of acidification, eutrophication and ground level ozone. For the STOCHEM model, methane emissions were based on the Intergovernmental Panel on Climate Change, IPCC (1995), assessment. The spatial distributions of oceans, tundra and wetland sources were estimated from the corresponding distributions of biospheric zones (Olson and Watts, 1982); anthropogenic sources were given the same distribution as NOx emissions (Benkovitz et al. 1995) and biomass burning and those of SO_2 were obtained from the same source (Spiro et al, 1992). Global hydrocarbon emissions from vegetation were taken from Hough (1991) and were distributed in space and time as for dimethyl sulphide from the corresponding soil and vegetation sources (Spiro et al., 1992). Soil NO_x emissions were taken from Yienger et al. (1995), and carbon monoxide emissions were taken from the literature review by Warneck (1988).

There have been a number of other independent studies, most of which are collected in the Proceedings from the 5th International Conference on Acidic Deposition, in Goteborg, Sweden, June 1995 (ACID REIGN '95?).

f. Global inventories

a.8 f.1 Major pollutants (S, C and N compounds, photo-oxidants and VOCs)

On a global basis the UN Framework Convention on Climate Change requires Parties to use the Revised 1996 IPCC Guidelines for National Greenhouse Gas (GHG) Inventories ("IPCC Guidelines"). All Parties to the Convention are to periodically make available to the Conference national inventories of anthropogenic emissions by source of all greenhouse gases not controlled by the Montreal Protocol. Parties are required to report emissions of all six Kyoto Protocol GHGs (CO_2, CH_4, N_2O, PFCs, HFCs and SF_6).

Also on a global basis, the Global Emissions Inventory Activity (GEIA) was created in 1990 to develop and distribute global emissions inventories of gases and aerosols emitted into the atmosphere from natural and anthropogenic sources. The long-term goal is to develop inventories of all trace species that are involved in global atmospheric chemistry. GEIA's mission is to provide high quality data for timely, relevant assessments. The requirements for a data set to be accepted as a GEIA data base include substantial peer review as reflected by acceptance for journal publication and agreement among the individual GEIA project teams. GEIA is a component of the International Global Atmospheric Chemistry (IGAC) Project, a core project of the International Geosphere-Biosphere Program. IGAC is a volunteer network of several hundred scientists in more than 30 countries who are working together to co-ordinate and stimulate efforts to measure, understand and predict changes in global atmospheric chemistry over the next century. The focus of GEIA is to make global emissions available on a one-degree grid for the entire world. Various scientific groups have taken responsibility for developing the inventories. The data are being collected for 1990 and are in

annual, seasonal or monthly resolution. Most data are provided for the surface level, but there is vertical resolution for some chemical emissions.

The data currently available at GEIA are Source-Specific Emissions (Nitrogen oxides in soils, NO_x lighting data, Volcanic Sulphur emissions), Compounds (Black Carbon from fossil fuel combustion and fossil fuel and biomass burning), CO_2 (fossil fuels), CFCs, Nitrous Oxide (annual and seasonal), reactive Chlorine Emissions, SO_2 (annual and seasonal), VOCs, natural data and other data such as population and cropland. Work being carried out by the GEIA program and the Norwegian Institute for Air Research (NILU) will determine the spatial distribution of heavy metals emissions and generate maps using data on anthropogenic sources from 1995 for Hg.

The Dutch National Institute for Public Health and the Environment, RIVM, found some uncertainties when compiling global emission inventories for SO_2, NH_3 and NO_x for their study. The Emission Database for Global Atmospheric Research (EDGAR) (Olivier et al., 1995, 1999) contains annual emissions estimates of greenhouse gases, ammonia, gases that affect ozone chemistry and depletion, and gases involved in aerosol chemistry and acidification from all known sources for 1990. Emissions from anthropogenic and biogenic sources are covered, providing the data set needed to estimate the total source strength of gases with a 1° x 1° resolution and a temporal resolution of one month. In the framework of the Global Emissions Inventory Activity (GEIA) and EDGAR in The Netherlands, a global emission inventory of CO emissions was compiled for 1990 with a 1° x 1° resolution (Olivier et al, 1999). The activity data was obtained from international statistics on fossil-fuel combustion, biofuel combustion, industrial processes, biomass burning, and other anthropogenic and natural sources. The major sources of global anthropogenic CO emission include agricultural waste burning, savannah burning, deforestation, road transport, and biofuel utilisation. Inventories of these species at 1° x 1° resolution and their uncertainties are discussed in detail in Olivier et al. (1996 and 1998).

g. Global distribution of emission sources

a.9 g.1 Sulphur compounds

Sulphur is mainly emitted as SO_2 by fossil fuel combustion and to a lesser extent from industrial processes and land use and waste treatment (in particular from biomass burning). A significant proportion of emissions are from natural sources, including volcanoes and algae in the oceans. An important part of anthropogenic SO_2 originates in East Asia (19%), USA (15%), Western Europe (15%) and the Former Soviet Union (12%) (Olivier et al. 1996 and 1998).

a.10 g.2 Nitrogen compounds

The main N substances emitted by human activities are nitrogen monoxide (NO) and nitrogen dioxide (NO_2) (together denoted as NO_x) and ammonia (NH_3). Global emissions of NO_x and NH_3 are discussed in detail in Olivier et al. (1996 and 1998) and Bouwman et al. (1997), respectively with natural emissions from soils being based on Davidson and Kingerlee (1997).

On a global scale, agriculture (principally livestock production) is by far the dominant source of NH_3, while industrial sources and fossil fuel combustion are the most important sources for

NO_x, with major contributions from natural sources (soils) and biomass burning. Regionally, this pattern is different. In regions with extensive natural areas, such as Canada, South America, western and southern Africa and Oceania, the contribution of natural ecosystems to emissions is more important than it is globally. In areas with large scale biomass burning (deforestation, savannah burning), such as South America, Sub-Saharan Africa, and South and South East Asia, this source contributes 19 to 40 percent to the regional NH_3 emissions and 37 to 47 percent to NO_x emissions.

a.11 g.3 Heavy metals and POPs

Heavy metals are released into the atmosphere by both natural and anthropogenic sources. Major anthropogenic sources of atmospheric heavy metals are fairly well recognised (combustion of fuels, industrial processes such as exploitation of mineral resources, mobile sources, tourism development and waste disposal). However more needs to be done to update emission rates and volumes and to generate better estimates of contaminant loads.

Persistent organic pollutants (POPs) form a class of persistent, bioaccumulative chemical substances which can result in adverse effects to human health and the environment at locations both near and far from their sources. Because they tend to be highly mobile in the environment as well as being resistant to degradation processes, POPs are prone to long-range transport and can accumulate in remote regions where they have never been used. It is now widely accepted that the use of such substances cannot be considered a sustainable practice and that concerted action needs to be taken to protect future generations.

a.12 g.4 Particulate matter

Fine particles are divided into primary and secondary particles. Primary particles are emitted by a source as particles and dispersed in the atmosphere without any major chemical transformation. Secondary particles are emitted as a gaseous pollutant (e.g. SO_2, NO_x) and react chemically in the atmosphere to form particles. For instance, SO_2 is oxidised to sulphate and forms with ammonia/ammonium, ammonium sulphate particles. Fine particles are found to be a constituent of six major categories (USEPA, 1996b): sulphates, nitrates, organic carbon, elemental carbon, trace metals, and water. Sulphates and nitrates are mainly secondary particles. For organic carbon, both primary and secondary formation is relevant. Elemental carbon and metals are usually emitted as primary particles. The main origins of primary particles are anthropogenic sources such as fuel combustion, road transport, industrial processes, domestic heating and wood combustion and natural sources such as soil dust and sea salt. The origins of secondary particles are mainly the oxidation of SO_2 and NO_x in fossil fuel combustion, volcanic emissions, vehicle exhaust, animal emissions and sewage.

1.2 EMISSIONS FORECASTS

a. Major pollutants (S, C and N compounds, photo-oxidants and VOCs)

On a global scale, the Intergovernmental Panel on Climate Change (IPCC) developed long-term emissions scenarios in 1990 and 1992. These scenarios have been widely used particularly in the analysis of possible climate change, its impacts, and options to mitigate it. In 1995, the IPCC 1992 scenarios were evaluated and it was recommended that significant

changes (since 1992), in the understanding of driving forces of emissions and methodologies, should be addressed. As future greenhouse gas (GHG) emissions are the product of very complex dynamic systems and their future evolution is highly uncertain, a set of scenarios was developed to represent them and described in the "Special Report on Emissions Scenarios", SRES (IPCC, 2000). Four different narrative storylines (A1, A2, B1, B2) were developed to describe consistently the relationships between emission driving forces and their evolution and add context for the scenario quantification. Each storyline originated and, therefore is composed of, a group of scenarios. The scenarios, which are representative of the literature, cover a wide range of the main demographic, economic, and technological driving forces of anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), hydrochloro-fluorocarbons (HCFCs), chlorofluorocarbons (CFCs), the aerosol precursor and the chemically active gases sulphur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOCs). For each narrative storyline several different scenarios were developed using different modelling approaches to examine the range of outcomes arising from a range of six models that use similar assumptions about driving forces.

The models used were:

- ***The Asian Pacific Integrated Model (AIM)*** (Morita et al., 1994, 1995) - a large-scale computer simulation model for scenario analysis of greenhouse gas (GHG) emissions and the impacts of global warming in the Asian-Pacific region.
- ***The Atmospheric Stabilisation Framework Model (ASF)*** (Lashof and Tirpak, 1990; Pepper et al., 1992, 1998; Sankovski et al., 2000) - includes GHG emission estimates and atmospheric models from energy, agriculture and deforestation for nine world regions (Africa, Central Asia, Eastern Europe, Latin America, Middle East, OECD-East, OECD-West, South East Asia and Oceania and the USA).
- ***The Integrated Model to Assess the Greenhouse Effect (IMAGE)*** (Alcamo et al., 1998; de Vries et al., 1994, 1999, 2000) - consists of three fully linked systems of models: the energy-industry system, the terrestrial-environment system and the atmosphere-ocean system. It is an integrated assessment model which computes the emissions of GHG in 13 world regions (Africa, Eastern Europe, Latin America, Middle East, OECD-Europe, CIS, South East Asia, India, China, Japan, Oceania, Canada and the USA) to evaluate the effectiveness of land-use policies, assess the land consequences of large-scale use of biofuels, evaluate the impact of climate change on global ecosystems and agriculture and investigate the effects of population, economic and technological trends on changing global cover.
- ***The Multiregional Approach for Resource and Industry Allocation (MARIA)*** (Mori and Takahashi, 1999; Mori, 2000) - a compact integrated assessment model to assess the interrelationships among the economy, energy, resources, land use and global climate change.
- ***The Model for Energy Supply Strategy Alternatives and the General Environmental Impact (MESSAGE)*** (Messner and Strubegger, 1995; Riahi and Roehrl, 2000) - an integrated assessment model that calculates cost-minimal supply structures under the constraints of resource availability, the menu of given technologies and the demand for energy.
- ***The Mini-Climate Assessment Model (MiniCAM)*** (Edmonds at al., 1994, 1996a, 1996b) - a small integrated assessment model that estimates global GHG emissions in

11 regions (Africa, Eastern Europe, Latin America, Middle East, OECD-Europe, South East Asia, Central Asia, Japan, Australia, Canada and the USA).

Each storyline assumes a distinctly different direction for future developments, such that they differ in increasingly irreversible ways. Two of these storylines (A1 and B1) describe a future world of very rapid global economic growth, one being more technology oriented (A1) and the other being focused on more clean technologies (B1). Their global population is based on the low International Institute for Applied Systems Analysis (IIASA) 1996 projection. The other two storylines (A2 and B2) describe a world focused on local and regional development which is also less technology oriented with population growth based on the long-term UN Medium 1998 population projection. This Report reinforces the understanding that the main driving forces of future greenhouse gas trajectories will continue to be demographic change, social and economic development, and the rate and direction of technological change.

In many SRES scenarios CO_2 emissions from loss of forest cover peak after several decades and then gradually decline. This pattern is consistent with scenarios in the literature and can be associated with slowing population growth, followed by a decline in some scenarios, increasing agricultural productivity, and increasing scarcity of forestland. Emissions decline fastest in the B1 storyline. Only in the A2 storyline do net anthropogenic CO_2 emissions from land-use change remain positive through 2100. Total anthropogenic methane (CH_4) and nitrous oxide (N_2O) emissions span a wide range by the end of the 21st century. Emissions of these gases in a number of scenarios begin to decline by 2050. The range of emissions is wider than in the IS92 scenarios due to the multi-model approach. Methane and nitrous oxide emissions from land use are limited in the A1 and B1 families by slower population growth followed by a decline, and increased agricultural productivity. After the initial increases, emissions related to land use peak and decline. In the B2 storyline, emissions continue to grow, albeit very slowly. In the A2 storyline, both high population growth and less rapid increases in agricultural productivity result in a continuous rapid growth in those emissions related to land use. The range of emissions of HFCs in the SRES scenario is generally lower than in earlier IPCC scenarios. Because of increasing awareness about the availability of alternatives to HFCs as replacements for substances controlled by the Montreal Protocol, HFC emissions are generally lower than in previous IPCC scenarios. In the A1 and B1 scenario families HFC emissions increase rapidly in the second half of the century, while in the A2 and B2 scenario families the growth of emissions is significantly slowed down or reversed in that period. Sulphur emissions in the SRES scenarios are generally below the IS92 range, because of structural changes in the energy system as well as concerns about local and regional air pollution. These reflect sulphur control legislation in Europe, North America, Japan, and (more recently) other parts of Asia and other developing regions. The timing and impact of these changes and controls vary across scenarios and regions. After initial increases over the next two to three decades, global sulphur emissions in the SRES scenarios decrease, consistent with the findings of the 1995 IPCC scenario evaluation and recent peer-reviewed literature.

There are various scenarios for future emissions of S and N compounds. Most of them project global emissions of acidifying pollutants to increase as a result of continued growth of human activities and fossil fuel consumption. However, regional trends differ markedly in the various projections. Internationally agreed abatement plans for sulphur dioxide and nitrogen oxides in Europe, and national plans in North America and Japan, will probably lead to a reduction in

emissions of acidifying pollutants in these regions. For other regions, however, significant increases are expected.

The main scenario used in the RIVM/UNEP study is the Current Reduction Plans scenario, CRP) (Stevenson et al., 1998) and is loosely based on the IPCC-IS92a scenario (Pepper et al. 1992; Houghton et al. 1992). The CRP scenario can be considered as a moderate-growth scenario. Emissions from fuel combustion, biomass burning and agriculture in 2015 were assumed to increase in most world regions. In contrast to IS92a for North America and Europe, emissions of sulphur dioxide and nitrogen dioxide were assumed to decrease by about 30-40 percent and 5-20 percent, respectively, in the period 1992-2015, corresponding to current policies within these regions. Outside these regions, however, emissions increase by more than 30 percent. Two more detailed scenarios have been constructed by Posch et al. (1996), taking into account the existing abatement plans for some regions.

The "no control" scenario of Posch et al. (1996) represents an extreme scenario because it is unlikely that industrialised countries will abandon their current laws for controlling emissions. Emissions in this scenario are considerably higher than the CRP scenario. In the case of the "partial control" scenario, emissions in Asia, particularly China, are still expected to increase rapidly, even though some controls were assumed. Emissions in Europe and North America decrease according to the "partial control" scenario by 24 percent and 25 percent, respectively, which is slightly lower than the CRP scenario. Full implementation of regional and national emissions policies within these regions might actually result in even lower emissions – up to 70 percent reduction in OECD Europe and 45 percent in Eastern Europe (Amann *et al*. 1997). In total, global emissions in the "partial control" scenario increase by 25 percent; under the CRP scenario, in contrast, they are assumed to increase by only 3 percent.

For anthropogenic NO_x emissions, the IPCC IS92a scenario projects an increase in emissions of about 30 percent between 1990 and 2015 (Pepper et al. 1992). This scenario has been presented on a grid-basis by Lee et al. (1997). In the IPCC IS92a scenario, almost no increase of emissions is projected for North America and Europe. Major increases are predicted for South, East and South East Asia, Middle East, Africa and Latin America. In the CRP scenario emissions are lower than those of the IS92a scenario, in particular, in Europe and North America, but also in other regions. Global emissions are assumed to increase by 13 percent.

A scenario has been constructed by FAO (1997) and Bouwman and Van der Hoek (1997) for NH_3 emissions from agriculture in developing countries. This indicates a sharp increase in N fertiliser use in developing countries from 50 Tg N per year in 1995 to close to 100 Tg N per year in 2025. Emissions from fertilisers are, however, expected to decrease by about a third as a result of assumed changes in the type of fertilisers used. At the same time, N in animal waste may double in 2025, causing a 60 percent increase in emissions. According to the CRP scenario, global NH_3 emissions will increase by 19 percent between 1992 and 2015.

b. Particulate matter

With regard to particulate matter, at European level, scenarios have been created that estimate the total European emissions of SO_2, NO_x and NH_3 for the year 2010 with reference to the year 1990. The REF (reference) scenario reflects current commitments covered by existing legislation and current reduction plans. The current Protocol is concerned with additional reductions beyond this point. The MFR scenario represents an estimate of the maximum feasible reduction if all possible technical abatement measures were to be implemented. In this sense it is a limit on what is technically available, disregarding costs of implementation. The intermediate scenario, called the G5/2 scenario, has been obtained using IIASA's RAINS model to calculate cost-effective patterns of emissions reduction to meet target improvements, for acidification, eutrophication and excess ozone (IIASA, 1999). The G5/2 scenario has been chosen as the starting point for the current negotiations as it has proved to be quite effective in reducing the contribution of SO_4, NO_3 and NH_4 to particulate exposure, as shown by results generated by the models used.

Scenario calculations for Europe for emissions of primary PM_{10} have been performed within the framework of preparation of the European Environment Agency's report (EEA, 1999). Emission projections for the year 2010 were prepared according to a number of scenario options, based on available economic and demographic components and the influence of environmental policy measures including the CLRTAP Second Sulphur Protocol and other measures relevant to primary particulates (EU regulations on particulates).

The Second Sulphur Protocol, under the CLRTAP, is the first protocol in force of relevance to emissions of primary particulates. According to Berdowski et al. (1998) implementation of this protocol will deliver emission reductions for PM_{10} from several important sources. One of the reasons for this is that secondary reduction measures, like Flue Gas Desulphurisation (FGD) for larger solid fuel-fired combustion plants, will lead to a significant reduction in the emission of particulates. Effective dust removal is essential for the correct operation of FGD, apart from the fact that the FGD process itself acts as de-dusting, thus further reducing emissions (the gases are spread by a liquid in order to remove the SO_2, and this will also remove PM). Another reason could be that primary measures, like the reduction of the sulphur content of liquid fuels, affect emissions since sulphur and ash content in the fuel and smoke production are related. The Heavy Metals Protocol under the CLRTAP will also have a beneficial effect on reducing emissions of PM_{10} from various important sources. Many heavy metals (HM) are emitted with particles and thus, when aiming to reduce emissions of HM, limits are also set for dust. The Heavy Metals Protocol includes limits for stack emissions from various industrial processes and large combustion plants. Additionally, the protocol on Persistent Organic Pollutants (POPs) and new protocols to abate acidification, eutrophication and ground level ozone are also thought to have positive side-effects for the reduction of primary PM_{10} emissions.

The uncertainty of the results means, however, that based on the "Business as Usual" (BAU) option, emissions are forecast to increase slightly during the period until 2010 compared to 1990 levels. Transport emissions will increase due to growth in this sector whilst changes in fuel types used will cause emissions from stationary sources to decrease. The "Policies in Place and Pipeline" (PIPP) option shows a significant reduction compared to BAU. The main reasons for this are the emission abatement in stationary combustion (due to, among others measures, the 2nd Sulphur Protocol) and more stringent emission limit values for vehicles. The largest reductions are expected to be achieved in Central and Eastern Europe. The use of "Best

Available Technology" (BAT), is expected to further reduce emissions to approximately one half of their 1990 levels. Further reductions compared to PIPP are achieved for emissions from production processes, stationary combustion and the transport sector. This is comparable to a very recent study done by IIASA (Johansson et al., 2000), which created two scenarios: the REF (Reference) and the MFR (Maximum feasible reductions).

2. ECOSYSTEM SENSITIVITY AND OTHER EFFECTS

Integrated Assessment models require relevant and effective methods for assessing the impacts of pollutants in the surrounding ecosystem, fauna and flora, and in human health. Although not without its critics, the critical load approach is generally considered the most appropriate method for assessing damage. The limit of air pollution concentration above which there may be a risk of damage is known as the critical level. The highest deposition of compounds that will not cause chemical changes leading to harmful effects on the ecosystem structure and function is defined as the critical load. This approach has been successfully applied in Europe in the framework of negotiations for the Convention on Long-Range Transboundary Air Pollution (see e.g. Hettelingh et al. 1995 and Posch et al. 1997).

The current aim of the RIVM Coordination Center for Effects (CCE) is to give scientific and technical support to the development of the critical loads and level methodology, in collaboration with the Programme Centres under the CLRTAP. Initially, CCE reports concentrated on the development of critical loads for acidification, eutrophication and critical levels for tropospheric ozone, which led to scientific support for the protocol on the further reduction of sulphur emissions (see Hettelingh et al., 1991; Downing et al., 1993) and of the second nitrogen oxide protocol. Subsequently, efforts to apply the concept were extended to related pollutants and multiple effects, and to heavy metals and POPs.

The CCE, as part of the Mapping Programme under the UN/ECE Working Group on Effects (WGE), collects critical load data from 24 individual countries and amalgamates them into European maps and data bases. These databases, together with scientific advice on critical threshold methodology, are made available to the integrated assessment modelling groups under the UN/ECE Working Group on Strategies (WGS). The latest critical loads data is being used for the current negotiations of a "multi-pollutant, multi-effect" protocol. Critical thresholds are also used in the RAINS model to assess emission reductions of acidifying and eutrophying pollutants as well as chemical oxidants in terms of costs and ecosystem protection.

2.1 ACIDIFICATION

a. Regional studies

Increasing industrial production, transport, agriculture and other economic activities result in higher emission levels of acidifying compounds, mainly sulphur and nitrogen. Acidification occurs when terrestrial ecosystems can no longer absorb the deposition of SO_2, NO_x and NH_3 without showing damage to soils and vegetation. Both sulphur and nitrogen compounds "compete" for neutralising base cations, which are mostly provided by deposition and weathering. The effects of acid deposition are widespread and appear in a number of ways,

including acidification of freshwater systems resulting in the loss of fisheries, impoverishment of soils, damage to forests and vegetation, corrosion of buildings, cultural monuments and materials. Moreover, man-made sulphur and nitrogen are precursors to the formation of small particles that impact on human health.

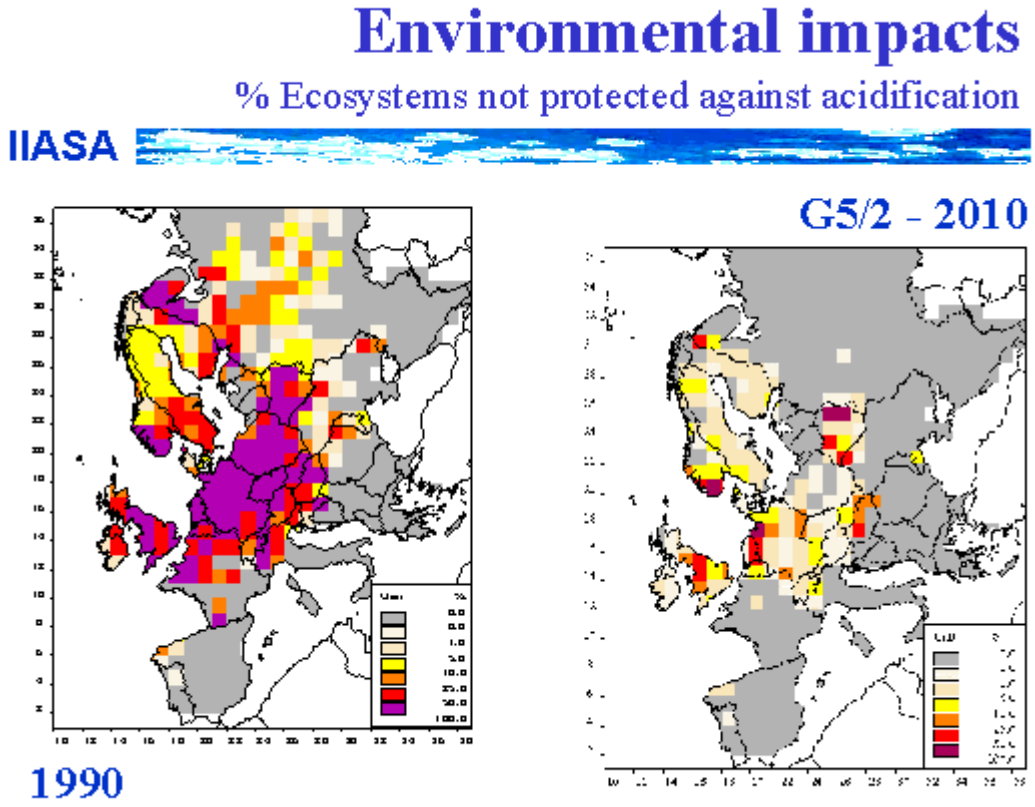
a.1 Europe

The critical load approach has been used in many regional and continental studies of acidification and eutrophication. In Europe, acidification is being studied within the framework of the UN Convention on Long-Range Transboundary Air Pollution. Data on emissions and air transport by EMEP and on the sensitivity of ecosystems by CCE is integrated by IIASA in the RAINS model. RAINS-optimisation scenarios directly support the negotiations under the Convention on future emission reduction obligations of countries in Eastern and Western Europe. Similar RAINS calculations are now also being made for Southeast Asia, within the RAINS-Asia project sponsored by the World Bank.

Using standardised methodologies, critical load data are compiled at national level. Each year, the Co-ordination Centre for Effects (CCE) located at the Dutch National Institute for Public Health and the Environment (RIVM) invites countries to submit revised critical load calculations. For most ecosystem types, critical loads are calculated for both acidity and eutrophication. Other receptor types, such as streams and lakes, have only critical loads for acidity, on the assumption that eutrophication does not occur in these ecosystems. For some receptors, like most semi-natural vegetation, only critical loads for nutrient nitrogen are computed since the sensitivity to acidifying effects is less than the eutrophying effects. For those countries who do not provide their national estimated critical loads to the CCE, the European background database for critical loads (de Smet et al., 1997) is used. This database is constructed using internationally published information, such as the 1994 digital soil map of FAO and the RIVM European land use maps. It provides for each cell of the EMEP grid system the cumulative distribution function of the critical loads for all ecosystems of the grid cell.

This has been mapped by RAINS; the results were that for 1990 emissions, acid deposition is calculated to exceed the critical loads mostly in the band ranging from northern France over Germany to the Czech republic and Poland. The emission reductions anticipated in the REF scenario are expected to significantly improve the situation and reduce unprotected ecosystems to a fifth. There is clear evidence that the overall area where critical loads are exceeded will decline, but that in other areas (northern Germany, southern Norway, Sweden, Hungary, and Kola (Russia)) there will not be such drastic improvements. In order to quantify targets for reducing acidification, RAINS has also been used to develop scenarios whose objective is to target acidification (G3 scenarios).

The following maps show the results obtained with RAINS for Europe for the years 1990 and 2010 (using the G5/2 scenario). (Source: IIASA)



a.2 North America

The US National Acid Precipitation Assessment Program, NAPAP (established as a result of the Acid Precipitation Act) project and other studies done by USEPA have examined in detail the effects of acid deposition in North America: on surface waters, forest, visibility, material and health. Lakes and streams were surveyed in the National Surface Water Survey, NSWS, with the results showing that acid rain is the cause of acidity in 75 percent of the acidic lakes and about 50 percent of the acidic streams. The regions in the US identified as containing many of the surface waters sensitive to acidification include the Adirondacks, the mid-Appalachian highlands, the upper Midwest and the high elevation West. Emissions from US sources also contribute to acidic deposition in eastern Canada, where the soil is very similar to the soil of the Adirondack Mountains, and the lakes are consequently extremely vulnerable to chronic acidification problems. Regarding acid rain contribution to forest degradation, the most affected are the high-elevation spruce trees along the ridges of the Appalachian Mountains. There is also concern about the impact of acid rain on forest soils, with evidence that long-term changes in the chemistry of some sensitive soils may have already occurred as a result of acid rain. Sulphur dioxide emissions lead to the formation of sulphate particles in the atmosphere with sulphate particles accounting for more than 50 percent of the visibility reduction in the eastern part of the United States. Because of health concerns SO_2 has always been regulated under the Clean Air Act. Sulphur dioxide interacts in the atmosphere to form sulphate aerosols, most of which are particles which can be inhaled, and which may be transported long distances through the air. In the eastern United States, sulphate aerosols make up about 25 percent of the inhalable particles. According to recent studies at Harvard

and New York Universities, higher levels of sulphate aerosols are associated with increased morbidity and mortality from lung disorders, such as asthma and bronchitis.

a.3 Other parts of the world

There are other regional studies of great importance, which analyse the local ecosystem sensitivity. One of these is the AMAP, which focuses on the eight Arctic rim countries (Canada, Denmark/Greenland, Iceland, Norway, Sweden, Soviet Union, and United States).

In other parts of the world, such as Australia, there is no evidence of significant acid deposition. Australia is not subjected to emissions from neighbouring countries and its fossil fuels have a low sulphur content (Commonwealth of Australia 1996).

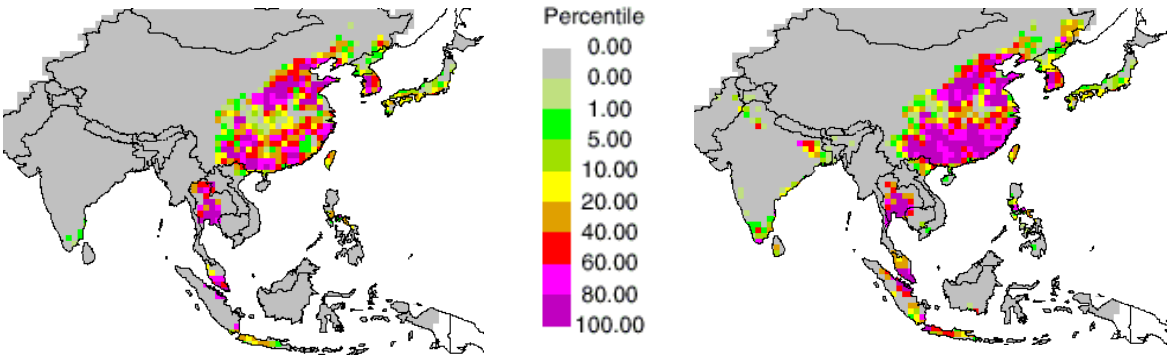
A great number of local and regional studies have focused on the analysis of acidification and its effects in several parts of the world. Some of these have been collected in Rodhe and Herrera (1988) and include studies assessing the effects of acid deposition on tropical terrestrial ecosystems (McDowell, 1988), and on tropical aquatic ecosystems (Galloway, 1988), etc. The sensitivity of the soils in some tropical areas is also outlined: Venezuela (Sanhueza et al, 1988), Brazil (Moreira et al, 1988), Nigeria (Isichei et al, 1988), China (Zhao et al., 1988) and Australia (Ayers et al., 1988).

Other studies have focused on the development and application of critical loads in other parts of the world, including South Africa (Van Tienhoven et al., 1995), Northern Asia (Bashkin et al., 1995), China (Xie, 1995), Japan (Shindo et al., 1995) etc. Most of these studies are collected in the Proceedings from the 5th International Conference on Acidic Deposition, in Goteborg, Sweden, June 1995 (ACID REIGN ' 95?).

The figures below show the sensitivity of Asian ecosystems to acidification used by RAINS-ASIA; the unprotected ecosystems with sulphur deposition above critical levels can be seen for 1995 and the year 2010 (assuming current legislation) (Source: IIASA)

Unprotected ecosystems with sulphur deposition above critical levels

1995 **2020 with current legislation**



b. Global Studies

More recently these issues have been studied on a global basis. A recent UNEP-RIVM study (UNEP/DEIA&EW/TR.99-6) aims to identify areas with potential acidification and eutrophication risks on a global scale. In this analysis recent simulation results for S and N deposition from the STOCHEM model (Collins et al. 1997; Stevenson et al. 1998) are used.

In the UNEP/RIVM study critical loads for acidification are based on soil properties. This study was based on the ecosystem sensitivity ranking of Cinderby et al. (1998) (also Kuylenstierna et al. 1998). The sensitivity of ecosystems was determined on the basis of soil buffering ability, which is itself determined from the soil's cation exchange capacity (CEC) and base saturation. The data on CEC and base saturation used were taken from Batjes and Bridges (1994) and Batjes (1997). Based on this, five sensitivity classes were formulated; this approach has been applied to the digital version of the FAO/Unesco Soil Map of the World (FAO 1995). A sixth class was used for all the areas where data on soil CEC and base saturation were not available. Contrary to Cinderby et al. (1998), who only accounted for S deposition, the combined assessment of S and N carried out by the UNEP/RIVM assessment indicates that areas away from highly industrialised areas may also be affected by acid deposition.

Critical loads for acid deposition were assigned to each of the sensitivity classes. A range of critical loads was employed expressing the uncertainty in the method used to determine soil sensitivity. The medium value is the one proposed by Cinderby et al. (1998). Two more extreme values were also used representing +50 percent and –50 percent, respectively, of the value for the medium class. The acidification risk is expressed as the exceedance ratio, i.e. the ratio of acid deposition : critical load.

The UNEP/RIVM study calculated the exceedance of critical loads for the world for 1992 for high, medium and low sensitivity (i.e. high, medium and low critical loads) for the current situation, and for the CRP scenario for 2015.

According to the results based on the medium estimates of critical loads, acidification is currently most prominent in the industrialised countries of Western Europe (38% of the area of (semi-)natural ecosystems affected), Eastern Europe (47%) and the eastern part of North America (USA and Canada). In addition, acid deposition exceeds critical loads in extensive parts of East Asia (16%) and South East Asia (23%). In most regions, a considerable share of the affected areas experience severe acidification risks (exceedance ratio > 2.0).

A much smaller fraction of the area of (semi-)natural ecosystems experiences acidification in the Former Soviet Union, Western and Central Africa and South America. Where exceedance ratios are greater than 1.0 in these regions, this is a result of high soil sensitivity, despite relatively low acid deposition rates. The study indicates that currently critical loads are exceeded in part of the south-eastern part of Brazil and the La Plata region, some parts of Siberia, the southern part of Western Africa, central Africa, the eastern part of China and parts of South East Asia. In some parts (in particular, tropical ecosystems) the high sensitivity of ecosystems causes exceedance, even at low N and S deposition rates. In total, net acid deposition exceeds the medium critical loads in about 10 percent of the world's (semi-)natural terrestrial ecosystems.

The UNEP/RIVM study also assesses potential global acidification in 2015, based on the Current Reduction Plans (CRP) scenario, which assumes moderately increasing emissions in most regions between 1992 and 2015, loosely following the IPCC IS92a scenario. In Europe and the USA, however, the scenario assumes decreasing emissions, thus incorporating existing policy targets and planned policy efforts within these regions. According to the CRP emissions scenario, acidification risks will decrease in Europe and North America. In other world regions (in particular, Siberia, China, South East Asia, Southern Africa) acidification will increase significantly, both with respect to the area affected and the severity of exceedance of critical loads. For the world as a whole, in 2015 net acid deposition will exceed the medium critical loads in 12 percent of the area of terrestrial (semi-) natural ecosystems. This means that in the relatively short time period covered (15- 20 years) the global problem of acidification could become more widespread and in some regions more intense.

2.2 EUTROPHICATION

a. Regional studies

Deposition of nitrogen-containing compounds also contributes to the eutrophication ("excess nutrient enrichment") of terrestrial and marine ecosystems. Their eutrophying effect is associated with increased leaching of nitrogen to groundwater, streams and lakes, and changes in the forest ecosystems leading to vegetation changes favouring nitrogen-tolerant species.

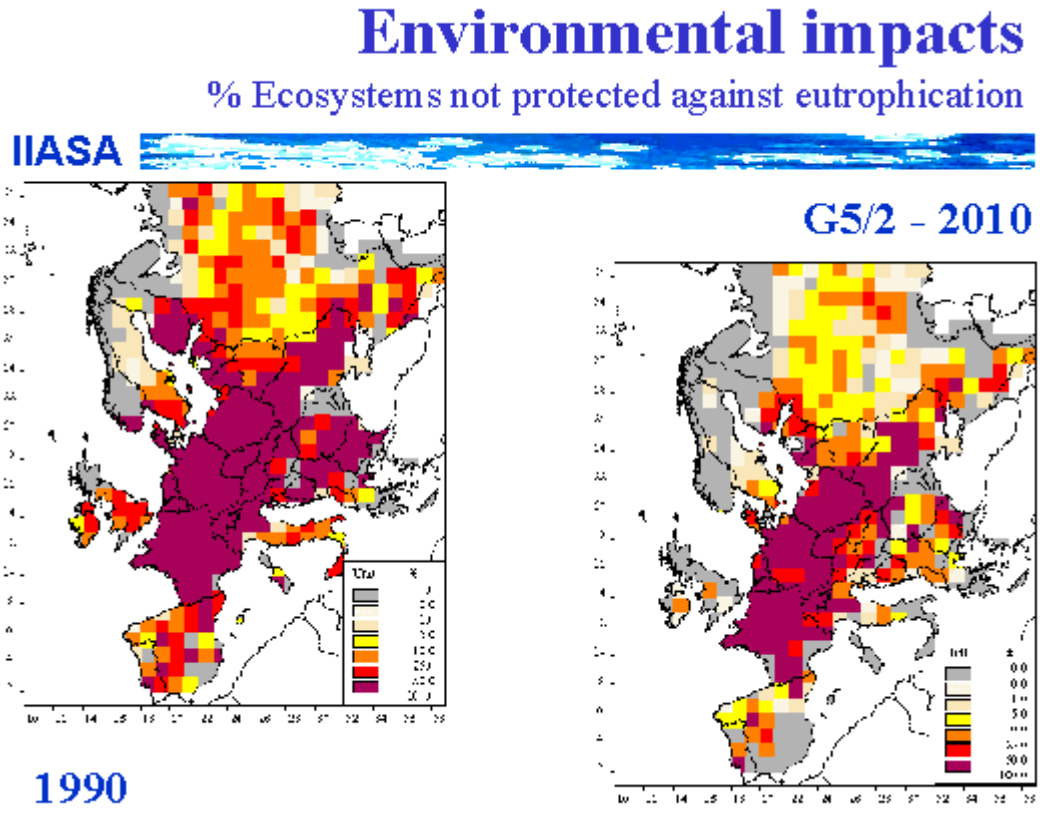
The paths of NO_x through the environment, and its impact, are much more complex than those of sulphur. In the presence of sunlight, NO_x combines with VOCs and carbon monoxide to form ozone - hence the need to negotiate controls on NO_x and VOCs simultaneously. Moreover, like SO_2, NO_x is also an important source of environmental acidification (responsible for about 20 percent in Europe, compared to 60 percent for sulphur and 20 percent for ammonia). But unlike sulphur, nitrogen is also a basic plant nutrient; it can be taken up by plants, often to excess, creating the problem of over-fertilisation, or eutrophication. Nitrogen from ammonia (NH_3) can have the same impact. This complex interaction makes it impossible to calculate a "simple" critical load value for an ecosystem. In reality, there can be no one fixed level. The total amount of acid deposition is important, but the ratio of sulphur to nitrogen can be equally important (depending on the ecosystem).

Nitrogen critical loads have been evaluated for specific groups of related ecosystems, including softwater lakes, wetlands and bogs, species-rich grasslands, heathlands, and forests by Bobbink et al. (1996). The studies have indicated that, to establish reliable critical loads, it becomes crucial to better understand the long-term effects of increased N deposition on ecosystem processes in a representative range of communities. Bobbink et al. (1999) also reviewed the impacts of increased atmospheric nitrogen (N) inputs on species diversity in natural and semi-natural ecosystems, with emphasis on freshwater systems, wetlands, grasslands, heathlands, and forests. Natural and semi-natural ecosystems contain higher biodiversity than altered landscapes, so nitrogenous atmospheric emissions must be controlled to prevent diversity losses. Further research on non-forested ecosystems is needed.

The RAINS EUROPE model has also been used for assessment of eutrophication in the context of the UNECE CLRTAP. Using the critical loads database compiled by RIVM, maps

of exceedance were created for eutrophication in Europe. The results showed that in 1990 eutrophication was a widespread phenomenon in many parts of central Europe, with the majority of grid cells in France, Germany, Poland, Romania and Bulgaria experiencing excess deposition for all their ecosystems. The emission reductions anticipated with the REF scenario will relieve the situation to some extent but will still leave millions of hectares unprotected. RAINS has also developed scenarios targeted at eutrophication (the G4 scenarios).

The following maps show the results for Europe obtained with RAINS for the years 1990 and 2010 (using the G5/2 scenario). (Source: IIASA)



The AMAP project has also been involved in the assessment of eutrophication in the Arctic region.

b. Global Studies

The UNEP-RIVM study (UNEP/DEIA&EW/TR.99-6) has also focused on the identification of areas with potential eutrophication risks on a global scale. In this study, critical loads for eutrophication are based on vegetation, soil and climate.

A review of available literature on effects of N deposition on natural and semi-natural vegetation in Europe is presented in Bobbink et al. (1996; 1998). Critical loads for N deposition were established following various expert meetings and, on the basis of these rules,

UNEP/RIVM extrapolated the critical load methodology to ecosystems outside of Europe. Using the land-cover/vegetation database from Olson et al. (1983), 0.5°x0.5° grid groupings were made, based on the expected sensitivity. Different classes were determined on the basis of soil and climate. Class 2 represents ecosystems with intermediate susceptibility, generally in moderate climates, and for soils with intermediate pH, base saturation and drainage. Class 1 includes ecosystems with high susceptibility to N inputs, generally caused by low soil pH, low base saturation, dry soil conditions, or permafrost. Class 3, for ecosystems with low susceptibility to enhanced N deposition, includes warm climates, soils with poor drainage (wet conditions), high base saturation and high pH. To assess the susceptibility of the analysis to variations in critical loads, ranges of critical loads were established by using high, medium and low values within each class on the basis of the range quoted in the literature.

The highest critical load values were assumed for tropical rain forests, tropical seasonal forests and mangroves (Bouwman et al. 1993; Vitousek et al. 1997). Other ecosystems, such as montane forests, tropical dry forests, savannah ecosystems, semi-arid woods, and scrub-rich and thorny vegetation types, have lower critical loads.

In the assessment of eutrophication risks, the three ranges of critical loads are used as alternative sets to evaluate sensitivity versus N deposition. The distribution of critical loads shows that for all three ranges, the regions with the highest susceptibility to N deposition are in northern Canada, Scandinavia and northern Russia. However, the extent of these regions is much smaller for the high range of critical loads than for the low range. Scattered regions of high susceptibility occur in South America and Africa. In tropical forests the low soil pH is the major cause of low critical loads, while in other regions the ecosystem itself (savannah and other dry and semi-arid vegetation types) has a high susceptibility, locally amplified by low soil pH. Intermediate susceptibility occurs in the western USA, Europe and Russia.

By comparing the three ranges of critical loads (low, medium and high) with the total N deposition, potentially affected regions can be identified. The affected regions were grouped on the basis of the eutrophication risk expressed as the exceedance ratio (N deposition divided by the critical load). It should be noted that vegetation types with a high surface roughness might actually experience higher deposition fluxes than those calculated for 5^o x 5^o grids. Hence, for a ratio of 0.75, the critical load may, under certain conditions, already be exceeded.

Areas in the various classes of the exceedance ratio are presented in the UNEP/RIVM study for the current situation, and for the CRP scenario for 2015. The location and extent of (agro-) ecosystems are assumed not to change between 1992 and 2015. In 7-18 percent of the global area of (semi-)natural ecosystems the exceedance ratio is greater than 1.0 for the medium estimates of the critical load. In particular, N deposition in OECD Europe exceeds critical loads (~30 percent of the area of (semi-)natural ecosystems), Eastern Europe (~60 percent) and North America (~20 percent of the USA and 5 percent of Canada) for the medium critical load. In the former USSR the affected area of (semi-)natural ecosystems is 9 percent for the medium critical load, mainly in remote tundra and taiga ecosystems.

Within the group of developing countries, Asian and African countries have extensive areas of (semi-)natural ecosystems where critical loads are exceeded by N deposition (South Asia, 32 percent, East Asia, 19 percent, South East Asia, 12 percent, Western Africa, 16 percent and Eastern Africa, 8 percent). According to the results for the medium critical load in Central

and South America, in 1 percent and 12 percent of the natural and semi-natural ecosystems, respectively, the exceedance ratio is greater than 1.0.

Following the CRP scenario, the areas with exceedance ratios>1.0 will not change significantly in most developed countries in the forthcoming decades; they will increase slightly in most tropical regions, including South America, Africa, South, East and South East Asia and Japan. The projected eutrophication risk differs from that for acidification, as in the CRP scenario no reduction plans were assumed for NH_3 gas emissions in Europe and North America, and emissions of NO_x stabilise.

2.3 PHOTOCHEMICAL OXIDANTS

Background concentrations of ozone in Europe are at least twice as high as they were a century ago. Excessive ozone in the lower atmosphere (tropospheric ozone, as opposed to stratospheric, or high-altitude, ozone) damages crops, weakens trees, and harms human health, especially in people weakened by bronchitis, heart disease, emphysema, or asthma.

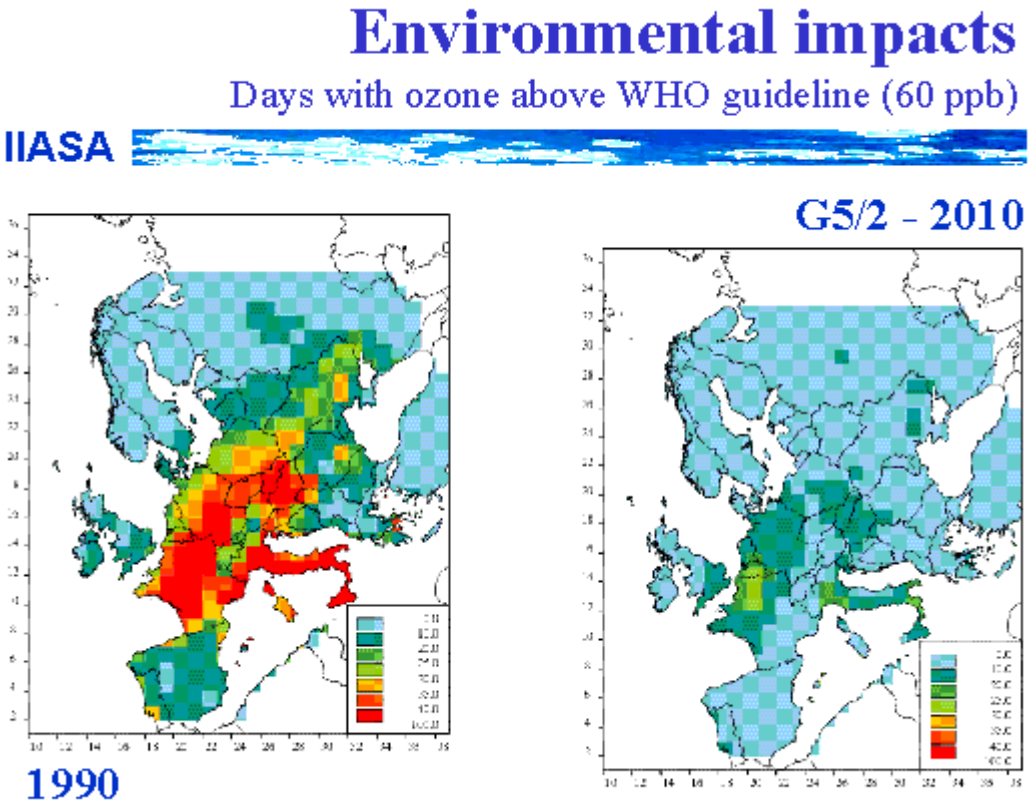
Tropospheric ozone is a secondary pollutant. It forms when nitrogen oxides, volatile organic compounds, and carbon monoxide mix in the presence of sunlight. Nitrogen oxide and carbon monoxide arise mainly from burning fossil fuels and volatile organics from solvents, paints, evaporating fuels and other chemicals.

Peak hourly or high percentiles of the hourly mean ozone concentrations are a useful indicator of the frequency and intensity of photochemical episodes and thus of the importance of ozone exposures to human health. However this approach is not always adequate for choosing ozone indicators for use in developing air quality policies. Critical levels have been defined for ozone in terms of accumulated time when ozone concentrations are above a particular threshold concentration (Karenlampi and Skarbi, 1996). For human health, WHO have recommended an air quality criteria value for ozone of 60 ppb, maximum 8-hour mean concentration, not to be exceeded more than once per year (WHO, 1996). However, this approach cannot easily be incorporated into integrated assessment models, and so for the purposes of IA modelling, the AOT60 concept is used as a surrogate for the 8-hour mean exposure measure (Bull and Krzyzanowski, 1997). AOT60 values in ppb.hours are calculated from hourly ozone records by summing all the concentration exceedances above a 60 ppb threshold, throughout a six month period. For impacts of ozone on crops, the critical level can be defined in terms of a threshold concentration of 40 ppb with an accumulated exposure of 3000 ppb.hours during daylight and the growing season between May and July. For forest, the critical level is defined with the same 40 ppb threshold but with an accumulated exposure, AOT40, of 10000 ppb.hours during all hours and the whole summertime period.

RAINS calculates the number of days on which the WHO health guideline value was exceeded by 1990 emissions. The most frequent excesses were recorded for Italy (60 days), northern France (50) and Germany (30-40 days). The REF scenario suggests emission reductions which are expected to have profound impacts on ozone exposure, with the maximum number of exceedance days expected to decline to 42 in France and 35 in Italy and

Germany. With respect to vegetation-related ozone exposures, the results show, for 1990, that in most countries the critical levels for vegetation were exceeded, the only exceptions being in some areas of the Scandinavian countries and of Russia. The most affected is the area extending from Paris over Belgium and The Netherlands to Germany. In many areas that do not experience significant exceedance of the AOT60, ozone levels exceed the AOT40 criterion considerably. This applies particularly to the Mediterranean countries and some alpine regions.

The following maps show the results obtained with RAINS for the years 1990 and 2010 (using the G5/2 scenario). (Source: IIASA)



Collins et al. (2000) has done a notable study in which a global 3-D Lagrangian chemistry model (STOCHEM) is applied to the formation of tropospheric oxidants and their influence on regional-scale formation and transport of photochemical ozone. STOCHEM generates a reasonably realistic picture of the present day distribution of ozone concentrations across Europe compared with observations from the EMEP ozone-monitoring network. For AOT60, STOCHEM shows maximum values in central Europe and steep gradients towards the Arctic. Ozone critical levels for crops are exceeded throughout Europe in all but the Arctic regions. Critical levels for forests are exceeded only in central and southern Europe, with a dividing line skirting southern England, including Denmark and southern Sweden and then dividing the Russian Federation. Peak exposures in the Alps and Italy are also spotted by STOCHEM and comparable with the measurements from EMEP. However, the tendency of the model to overestimate AOT60 and 40 levels should be taken into account; the observed European area-

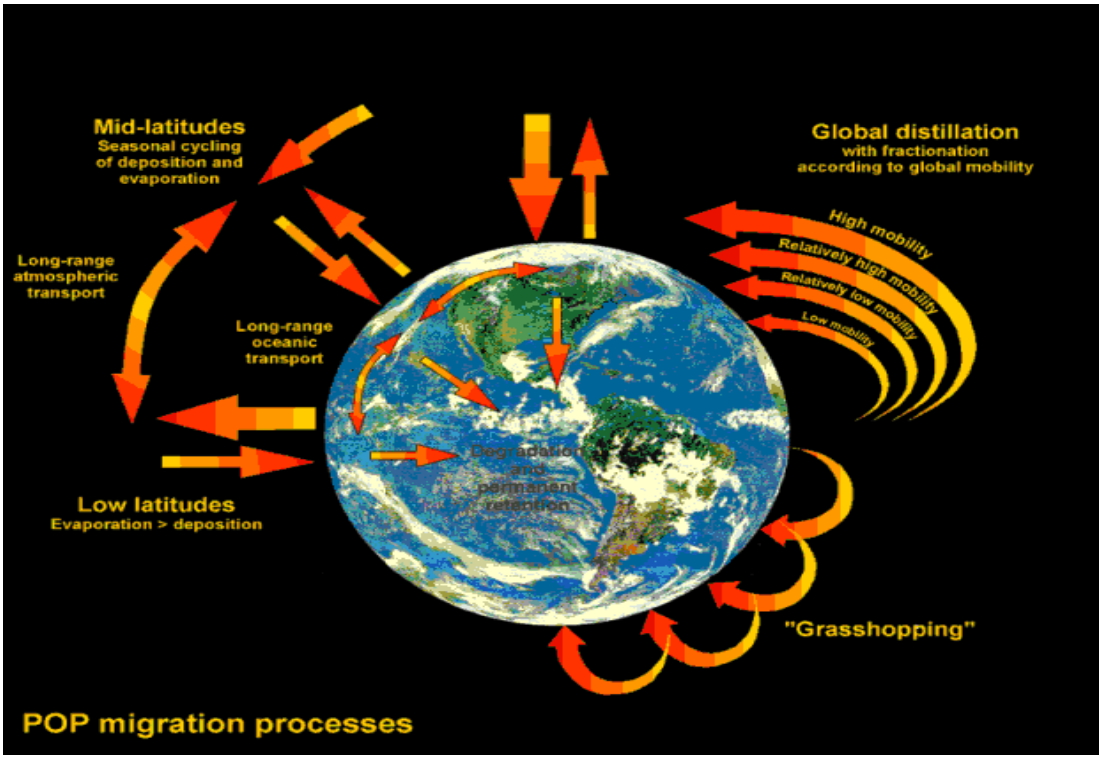
weighted mean AOT60 and AOT40 exposures over the EMEP network are, respectively, 2700 and 6500 ppb.hours, compared with 3800 and 7100 ppb.hours in the model calculations.

STOCHEM was also used to create maps of O_3 distributions across Europe for the year 2015 under three possible scenarios. In the base case, maximum O_3 concentrations were just under 75 ppb with the 50 ppb contour passing through the Arctic regions and up the Atlantic coast fringes of Europe. In the BAU scenario, maximum concentrations increase up to 86 ppb. This increase is almost removed in the CRP scenario where the maximum value is 73 ppb, and decreases to under 70 ppb for the MFR scenario. It can be seen, therefore, that the WHO air quality standard AOT60 is likely to be exceeded throughout much of continental Europe, although it is unlikely to be exceeded in the UK and Scandinavia. The target of reducing AOT40 exposures appears to be infeasible over the entire northwest and central Europe. Only the Arctic areas of Norway, Finland and Russia have substantial areas where the ozone critical level is not exceeded. The situation in 2015 is caused by the global growth in man-made methane, hydrocarbons, NO_x and carbon monoxide emissions leading to increased baseline tropospheric ozone concentrations. These increased baseline concentrations are so close to the AOT40 threshold concentration, that regional photochemical ozone production can still lead to exceedance of ozone critical levels despite large reductions in European NO_x emissions. Action on a global scale will be required to control ozone precursor emissions other than NO_x if ozone critical levels are to be reached in the year 2015 across Europe.

2.4 HEAVY METALS AND POPs

De Vries et al. (1998) estimated the critical loads of lead, cadmium, copper, zinc, lindane, and benzo(a)pyrene for forest soils in The Netherlands to facilitate utilisation of the critical load approach in the international heavy metal and POP abatement policies. The atmospheric deposition risk for these diverse substances in forest soils of The Netherlands was defined on the basis of the difference between the computed current atmospheric loads and critical loads determined from modelling and experimentation. Calculated values for the critical loads are significantly influenced by the type of environmental quality criterion that serves as the basis for the calculation. Greater detail on the quality criteria is needed to provide essential insights into the risk associated with loads of heavy metals and POPs on terrestrial ecosystems.

The following picture shows the migration processes of POPs in the globe (source:AMAP):



2.5 OTHER EFFECTS ON HEALTH, MATERIALS, CROPS AND VISIBILITY

Besides the effects of pollutants on the ecosystem, which was the original focus of integrated assessment, there are other effects that should be taken into account, in particular, the major effects that all these pollutants can have on human health. The UK Atomic Energy Authority, AEAT, has analysed the benefits that the reduction of emissions of pollutants can effect on health, materials, crops, forests and other ecosystems and visibility (Holland et al., 1999).

a. Health

Two types of effect on human health can be distinguished: acute and chronic effects. Acute effects are those that arise from short-term exposures to air pollution. Exposure response functions for them are calculated from observations of daily fluctuations in concentrations of air pollutants, compared to daily variation in the incidence of death or disease. Chronic effects, in contrast, arise from long term exposures. Exposure-response functions can be calculated by comparing annual concentrations of pollution against age at death, or against the incidence of diseases, such as bronchitis, which are long-term in nature. Both acute and chronic effects can have an impact on mortality and morbidity. Acute effects on morbidity include bronchodilator usage, cough and lower respiratory symptoms in asthmatics, asthma attacks, respiratory hospital admissions, congestive heart failure, cerebrovascular hospital admissions (stroke), restricted activity days, minor restricted activity days, etc. Chronic effects on morbidity could be incidence of bronchitis or cough.

NO_3 and SO_4 aerosols have both acute and chronic effects on mortality and morbidity and are fairly well documented in the literature. Ozone has effects on both acute mortality and

morbidity. With respect to SO_2, there is considerable data regarding acute effects. There is also evidence, though not very well documented, of the effects of VOCs on human health dependant on VOC specification.

a.13 a.1 Acidifying pollutants

Under the NAPAP assessment, the USEPA has produced an exhaustive study on the quantification of health effects of acidifying pollutants (mainly sulphate) through a series of epidemiological and field studies, human clinical studies and laboratory and toxicological studies. The main findings are the following:

- ***Premature mortality.*** Evidence has been found in prospective cohort and cross-sectional studies of an association between mortality rates in different locations and average sulphate concentrations in those locations (e.g., Pope et al., 1995). Evidence has also been found in time-series studies of an association between daily mortality rates and sulphate concentrations in several urban areas in the United States and elsewhere (e.g., Dockery et al., 1992).

- ***Chronic respiratory disease.*** Prospective studies have found higher rates of chronic respiratory disease in locations with higher PM concentrations (e.g. Abbey et al., 1995a,b).

- ***Hospital admissions.*** Time-series studies show a correlation between daily hospital admission rates and daily sulphate concentrations (e.g. Burnett et al., 1995).

- ***Aggravation of asthma symptoms.*** Time-series studies with panels of diagnosed asthmatics who record their symptoms and medication usage each day have found an association between the aggravation of asthma symptoms and daily sulphate concentrations (e.g. Ostro et al., 1991).

- ***Restricted activity days.*** The frequency of such days has been found to be significantly associated with the average $PM_{2.5}$ concentrations in the city of residence during the same 14-day period (e.g. Ostro and Rothschild, 1989).

- ***Acute respiratory symptoms.*** The frequency of such symptoms was found to correlate with daily sulphate concentrations in the study location (e.g. Ostro et al., 1993). Taken as a whole, the available epidemiology evidence shows a strong relationship between sulphate aerosols, and other fine particulates, and respiratory-related illness in the United States. The types of illness range from the severe acute and chronic illnesses associated with increases in risk of death to mild acute symptoms such as coughing and wheezing. There is epidemiological evidence of health effects for both short-term fluctuations in sulphate concentrations within a given location and long-term variations in sulphate concentrations across locations.

a.14 a.2 POPs

AMAP focused on the study of pollutants in the Arctic and their effects, and has held a number of workshops focusing on the effects on human health and ecosystems of pollutants

such as heavy metals and POPs. Persistent organic pollutants (POPs) can result in adverse effects to human health and the environment at locations both near and far from their sources. In addition to the adverse acute effects that can result from accidental exposure or ingestion, various chronic effects can result from long-term, low-level exposure; these include increased cancer risk, damage to the central and peripheral nervous systems, reproductive disorders, disruption of the immune system and interference with normal infant and child development.

Some POPs are also thought to be endocrine disrupters which, by altering the hormone system, can damage reproductive and immune systems of both exposed individuals and their offspring. The most readily available information on the effects of heavy metals is at the level of individual tissues. Based on laboratory studies, observed levels of Cd and Hg in some Arctic marine birds and mammals are high enough to be of concern. However, observable effects in wild animal populations have been more difficult to find. Exceptions exist in heavily contaminated sites such as Minamata, Japan, where acute mercury related effects were seen in human and wildlife populations due to high industrial discharges of mercury. An objective of AMAP and all the countries involved in the project is to continue investigating the effects of heavy metals and POPs on fish, birds, plants, mammals and the ecosystem.

a.15 a.3 Particulate matter

The clear link between particulate matter and health has already been noted. There is also evidence that several emission sources contribute to concentrations of fine primary and secondary particulate matter in ambient air. Therefore, when addressing health-related issues relating to fine PM and when looking for cost-effective solutions to control them, primary emissions should be taken into account, as well as the precursors of secondary aerosols. This could be seen as an extension of the multi-pollutant multi-effect concept applied to acidification, eutrophication and ground level ozone.

Early epidemiology studies attributed increases in daily deaths to severe episodes of high pollution. For example, the smog which affected London in December 1952 (UK Ministry of Health, 1954) was responsible for 4700 additional deaths; pollution levels (measured as BS) reached 4000 $\mu g/m^3$, and there was a fivefold increase in mortality on high-pollution days. This episode finally spurred the Government into action and led to the Clean Air Act 1956. This Act, which was amended in 1968, regulated pollution from smoke, grit and dust from domestic, commercial and industrial sources. Other well-documented severe episodes have occurred in the Meuse Valley (Belgium) in 1930 and in Donora (US) in 1948.

Several studies have focused on the health effects of long-term exposure to particulate matter but only a few have applied exposure assessment methods allowing quantification of the impacts. Two studies, which were conducted in the United States, indicate an association of mortality with the long-term average pollution level in the place of residence. One of these, the Harvard Six-cities study (Dockery et al., 1993), suggests that the concentration of sulphates and fine particles is a better predictor of mortality than coarse particle fraction or TSP. The second study, (Pope et al., 1995), concentrated on fine particulates and sulphates only.

These analyses indicate that children may be more susceptible to the mortality effects of air pollution exposure than the population in general, but it is difficult, given the limited research

available, to associate this to PM pollution, in particular. This is an area where further research is clearly needed.

Several of the hospitalisation studies restricted their analysis by age of the individuals, but did not explicitly examine younger age groups. One exception was Pope (1991) who reported an increase in hospitalisation for Utah Valley children (aged 0 to 5) for monthly numbers of admissions in relation to PM_{10} monthly averages, as opposed to daily admissions in relation to daily PM levels used in other studies. Studies by Thurston et al. (1994) and Burnett et al. (1995), which examined acid aerosols and sulphates, showed results differing by age.

b. Materials

The materials considered in this study are: sandstone, limestone, mortar, brick (for which no effect has been assumed), cement (again, for which it is assumed that there is no effect), galvanised steel, zinc, aluminium (assumed too corrosion resistant for significant effects) and paint.

Climate, in terms of rainfall, changes in temperature, exposure to sunlight etc, all result in the loss of material from the surface of buildings over time. Air pollution, particularly SO_2, increases the rate of this process. Effects have therefore been assessed for exposure to SO_2 and acidity. Ozone is also known to damage materials (Holland et al, 1998), with effects on paint and rubber probably most prominent. These could not be assessed here because of the lack of an inventory of the stock at risk at European level.

c. Agriculture and forest decline

Effects on agriculture were calculated for a wide range of crops and also for cattle, milk production and sheep. Together these cover virtually all the pollution-sensitive agricultural production (by value) across Europe. Five types of effect were included in the analysis: direct and indirect effects of O_3 on crop yield, effects of SO_2 on crop yield (which may be positive or negative with increasing concentration, depending on the supply of nutrient sulphur from the soil), changes in livestock and milk production through changes in pasture productivity, acidification of farmland, leading to a requirement for additional liming and fertilisation of farmland with nitrogen.

Forest decline was one of the earliest drivers for action to control transboundary air pollution in Europe. However, quantitative assessment of effects of ozone and acid deposition on forests remains difficult, despite the wealth of experimental data available on the effects of pollution on plant material. Only one aspect of the problem was assessed by AEA: loss of timber production from exposure to ozone. No account was taken of the effects of acidification and eutrophication on forests.

d. Visibility

Fine particles and NO_2 in the atmosphere have important effects on the transmission of light, resulting in a decrease in visual range. This results in a loss of amenity as a consequence of the loss of enjoyment when viewing scenery, buildings, etc. This has given rise to much

concern in the USA in particular, though relatively little in Europe. Valuation data are taken entirely from studies carried out in the USA.

2.6 INTERACTIONS BETWEEN DIFFERENT ENVIRONMENTAL STRESSES

a. Acidification and eutrophication

In many regions eutrophication and acidification occur simultaneously. However, regionally there are important differences. Where acidification and eutrophication occur simultaneously, their combined effect may create significant stress in (semi-)natural ecosystems.

Available emission scenarios suggest that in many tropical regions S and N emissions may increase significantly in the near future and that problems of acidification and N eutrophication may aggravate and expand over larger areas in these regions. In many cases the two problems occur simultaneously as result of high deposition of N. However, there are also significant differences between the two risk areas. In general, acidification is more localised in industrialised areas than eutrophication (because a major source of N deposition is agriculture). As a result, in South America, for instance, large areas are at risk from eutrophication, while the risk from acidification is low. The most striking differences occur in Japan and Canada (where the area with exceedance of critical loads for acidification is larger than that for eutrophication) and South Asia (where there is very little acidification but high risk of eutrophication). There may be three reasons for the differences:

1. Deposition of S (which contributes to acidification but not to eutrophication).
2. Differences in soil and ecosystem susceptibility (including the processes of immobilisation and denitrification).
3. Deposition of base cations.

In the case of India, both 2) and 3) play an important role, resulting in low acidification risk. In Canada and Japan differences are caused by the relatively high sensitivity to acidification and high S deposition. Where acidification and eutrophication risks occur simultaneously, their combined effect may put significant stress on existing ecosystems.

b. Acidification and climate change

The impacts of acidification and eutrophication are in reality closely linked with other environmental stresses, including climate change. Hence, in future studies not only should S and N deposition be addressed, but also climate change and rising atmospheric CO_2 concentrations.

Eutrophication studies could then also consider effects of increasing N inputs, changing climate and the CO_2 fertilisation effect on ecosystem net primary production, and emissions of N gases such as nitrous oxide and nitrogen oxides.

Earlier models of climate change, including that used by the United Nations Intergovernmental Panel on Climate Change (IPCC), have tended to exaggerate the actual rate of global warming (Charlson et al., 1994). One explanation for this discrepancy is that emissions of SO_2 or sulphate aerosols have atmospheric cooling properties; thus SO_2

emissions perform a beneficial function in slowing down or offsetting the rate of global warming caused by emissions of greenhouse gases. This should be taken into account when creating integrated assessment models: policies to abate emissions of SO_2 should impose a social cost in terms of a lost atmospheric cooling effect.

However, the exact effects of these cooling properties are as yet not very well understood and the imprecision of forecasts of climate change have only stimulated research into these cooling effects. Scientists have sought to link the increasing occurrence of atmospheric sulphate aerosols with their underprediction of climate change. Although still at an early stage, researchers have identified two main effects:

- In the ***direct effect***, the aerosols enhance the ability of the atmosphere to reflect some of the incoming solar radiation (Charlson et al., 1994). The greenhouse effect operates where incoming solar rays are reflected back from the earth, but are trapped in the atmosphere by the greenhouse gases (e.g. CO_2). The aerosols reflect some of the incoming radiation, which cannot, therefore, participate in the warming process. Less warming, therefore, means some cooling.
- The ***indirect effect*** works on cloud reflectivity by affecting nuclei densities. Aerosols act as nuclei for condensation and the density of these nuclei determines the number and size of cloud droplets. Charlson et al., (1994) suggests that a 30% increase in cloud reflectivity could counteract the average warming caused by anthropogenic CO_2 increases during this century.

Quantification of these direct and indirect effects requires more research. So far, the empirical evidence that has emerged suggests that aerosols produce a net cooling effect in local regions of the eastern US, south-central Europe and eastern China. These are the regions in which the largest SO_2 emissions are located.

3. LONG-RANGE TRANSPORT AND DEPOSITION

3.1 REGIONAL STUDIES

a. Europe

a.16 a.1 Acidification and eutrophication

The use of models for the study of long-range transport and deposition of pollutants is most advanced in Europe. The CLRTAP brings together several tools and research groups to assess the long-range transport of pollutants and examine how emissions from a certain area are deposited far from the source and impact on other areas. The CLRTAP delegated to EMEP preparation of maps of deposition of acidifying and eutrophying substances in Europe, as well as photo-oxidants, POPs and heavy metals. One of the activities of EMEP MSC-E is to provide countries/parties to the Convention with information on source-receptor relationships. Full country-to-country deposition matrix can be found in the different EMEP reports, e.g. Ryaboshapko et al. (1999) for heavy metals. The source-receptor relationships demonstrate the long-range transport of Pb, Cd and Hg. Concentration and deposition fields for these heavy metals are also a result of the EMEP work on them and can be used by modellers for

further work. Similar work has been done, and is being further developed, for the EMEP POPs model.

Until 1998, the 2-D Lagrangian Acid Deposition model was routinely used at EMEP/MSC-W. In 1999 the 3-D Eulerian Acid Deposition Model was applied to calculate air concentration and deposition fields for major acidifying and eutrophying pollutants as well as their long-range transport and fluxes across national boundaries.

The EMEP Lagrangian Acid Deposition Model (LADM) is a receptor-oriented one layer trajectory model. Since 1985 it has been used at the EMEP/MSC-W to calculate concentrations and depositions of acidifying compounds in Europe, as well as transboundary fluxes and budget matrices. The model, which has been comprehensively described in a number of publications, is formulated on a polar-stereographic projection and has a horizontal resolution of 150x150 km^2. The LADM uses annual officially reported SO_2, NO_x and NH_3 national emissions disaggregated on the 50x50 km^2 EMEP grid (see e.g. Olendrzynski, 1997). The GENEMIS country-specific database is used to calculate the expected monthly proportions of the total emissions. The most recent updates of the emissions used to compute the transboundary fluxes presented here are documented in Mylona (1998). The meteorological data required for calculation of trajectories, chemical coefficients and wet and dry deposition, is obtained from the Numerical Weather Prediction model of the Norwegian Meteorological Institute or analysed from observations (Jakobsen, 1996). Land-use data required for calculating the dry deposition velocity was provided by RIVM. The Lagrangian model has been routinely verified against measurements at EMEP sites (Iversen et al., 1990; Iversen, 1990 and 1993; Sandnes, 1993, Tarrason et al., 1998). A comprehensive evaluation of the model performance has been carried out based on a comparison between 12-year series of modelled and monitored air and precipitation concentrations (Tsyro, 1998).

The Eulerian acid deposition model has been developed at MSC-W as a multi-layer model for simulating the atmospheric transport and deposition of nitrogen and sulphur compounds in Europe. The first version of the EMEP Eulerian model was developed by Berge (1993) and then modified and further improved by Jakobsen et al. (1995). Nitrogen chemistry was introduced into the model by Jonson and Berge (1995) and a new dry deposition module for SO_2, NO_2, HNO_3 and NH_3 was implemented by Jakobsen et al., (1996). The model was run for 1992 and the results compared with measurements available from the EMEP stations in Europe (Jakobsen et al., 1995). Model validation for 1996 data is described in Olendrzynski et al., (1998). The changes to the EMEP Eulerian acid deposition model, made in 1999 for the runs with the 1997 data, are discussed in detail by Olendrzynski in EMEP/MSC-W Note 4/99. The computed 1997 air concentrations and depositions for major components are presented in the form of maps. The respective scatter diagrams illustrate the agreement between model computations and measurements at EMEP measurement stations.

The source-receptor matrices obtained by EMEP have been used by other models, such as RAINS-EUROPE, in order to better estimate and predict depositions within the region under the CLRTAP. RAINS estimates deposition of sulphur and nitrogen compounds as a result of emissions in each country, and then sums the contributions from each country with a background contribution to compute total deposition at any grid location.

The STOCHEM model has also been used for the calculation of sulphur deposition across Europe. It was found that its results coincided with those obtained from EMEP. The STOCHEM model uses as input emissions of S and N, based on scenarios of economy, population and emission factors.

Most of the models show the same results with the largest depositions being found in high emission areas, such as the Black Triangle region in Central Europe. The long-range transport of these pollutants has been shown to cause deposition in areas that are not important sources. The exceedance of critical loads measures the damage that is done to the different ecosystems. For instance, although deposition and concentration is lower in north western Europe, the ecosystems in these areas are more sensitive, and therefore damage can be caused even if there is little deposition. In the Mediterranean regions, the ecosystems are not so sensitive, and can tolerate higher deposition with little or no damage.

a.17 a.2 Ozone

The EMEP Eulerian photochemistry model has been designed as an extension of the EMEP Eulerian acid deposition model. The basic model description for the EMEP Eulerian acid deposition model is, with a few exceptions, also valid for the EMEP Eulerian photochemistry model. The differences between the two models are related to dry deposition and the formulation of the chemistry. A description of the basic model formulations can be found in Bartnicki et al. (1998).

The EMEP ozone model has been described in detail elsewhere (Simpson, 1992, 1993, 1995). Briefly, the model is a one-layer Lagrangian model that follows parcels of air along 98-hour long trajectories, picking up emissions of NO_x, VOC, SO_2 and CO from the underlying grid. The model as a whole has been compared with four other European models for July 1985 and an episode in July 1990 (Builtjes et al. (1991), Hass et al.(1996)). The EMEP model was found to compare favourably with more complex models in terms of comparison with measurements, although the short-time periods of these comparisons makes any generalisations difficult. The meteorological data used are routinely produced and archived by MSC-W for use in EMEP long-range transport models, including the oxidant model. These data are obtained from the Norwegian Meteorological Institute's numerical weather prediction (NWP) model, which is described in detail in (Grønås and Hellevik, 1982), (Grønås and Mitbø, 1986), and (Nordeng, 1986).

The formation of ozone involves chemical reactions between NO_x and VOC driven by solar radiation and occurs on a regional scale in many parts of the world. The time scale of ozone production is such that ozone concentrations build up in polluted air over several days under suitable weather conditions, and this pollutant and its precursors can be transported over considerable distances and across national boundaries. An IA model for ozone needs to be able to relate ozone exposure to changes in the emissions of ozone precursors. For application in an IA model, however, the source-receptor relationships need to be valid for a variety of spatial patterns of emission sources and for a range of emission levels and not restricted to present-day situations alone (Amann et al., 1998). For that reason, attempts to define these relationships only on the basis of recent ozone measurement data are likely to prove inadequate. The ozone formation description needs to be based on mathematical models that have gained widespread acceptance. Most of the available models for ozone formation are

process-oriented and contain considerable detail of the chemical mechanisms and meteorological factors relevant for ozone formation. Consequently, their computational complexity makes it impossible for use directly with the framework of IA model. In order to overcome this, EMEP has constructed a reduced-form model - the EMEP ozone model (Simpson. 1993). This EMEP model was selected by RAINS to analyse ozone formation because its results have been validated with other models and it is capable of calculating ozone levels all over Europe over a time period of six months.

The STOCHEM model has also been used for the calculation of ozone concentrations across Europe. It was found that its results coincide with those obtained from EMEP.

Several studies have been conducted in recent years looking at photochemical production of O_3 over Europe, including the Testing Atmospheric Chemistry in Anticyclones (TACIA); this investigated the impact of European emissions on background O_3 and in particular whether O_3 production is NO_x limited or VOC limited.

a.18 a.3 Particulates

The Protocols currently in place under the CLRTAP aim to abate acidification, eutrophication and ground level ozone, with the objective of reducing emissions of SO_2, NO_x, VOCs and NH_3. Although these Protocols have not directly addressed the reduction of particulate concentrations and health effects, it has been shown that the base-case scenario under discussion for negotiations is also quite effective in reducing exposure to secondary particulate SO_4, NO_3 and NH_4. There will also be some benefits for primary particulate matter reduction, though these are less readily quantifiable. Based on this, models have been used to examine the reductions in particulate concentrations and population exposure as a result of international agreements and current reduction plans.

The EMEP Lagrangian Acid Deposition Model (EMEP-LADM) (EMEP 1998a, EMEP 1998b) creates maps of annual average SO_4, NO_3 and NH_4 concentration fields over Europe. It also creates maps of source attribution of those concentrations in the different countries, i.e. contributions to the particulate concentrations in each grid square per tonne of emission from each country. This has provided the source-receptor matrices used to analyse future emission scenarios, which form the basis for international negotiations of emission reductions under the CLRTAP. It should be noted that the EMEP-LADM has been designed to simulate and analyse the atmospheric transport of sulphur and oxidised and reduced forms of nitrogen, and not specifically to calculate SO_4, NO_3 and NH_4 contributions to secondary particulate matter concentrations. Comparisons with measurements show that the EMEP- LADM model tends to over-estimate particulate concentrations, especially for the nitrate component where the modelled values are on average about twice the observed values. Some of this disparity may be due to the measurement techniques, which often do not reflect the total nitrate content (APEG report, Harrison et al., 1998).

The aim of the second Sulphur protocol (Oslo, 1994) under the CLRTAP is to bring about further reductions of SO_2 emissions across Europe. Three models were used in the development of this protocol (ApSimon et al., 1996) under the Task Force on Integrated Assessment Modelling (TFIAM): the RAINS model of the International Institute for Applied Systems Analysis (Alcamo et al., 1990), the CASM model of the Stockholm Environment

Institute (SEI, 1991) and the Abatement Strategies Assessment Model, ASAM, of Imperial College (ApSimon et. al, 1994). These models used source-receptor matrices calculated from the EMEP-LADM model to estimate, among others, scenarios mapping concentrations of secondary particulates for different years. Although each model has its strengths and weaknesses, all have been used to optimise the distribution of emission reductions in different countries in order to reduce deposition to meet pre-determined target loads at least cost.

ASAM calculates emission abatement strategies, specifically aimed at reducing secondary particulate exposure (SO_2, NO_x and NH_3) by (ApSimon et al., 1994) taking a step by step approach to derive a sequence of abatement steps across the different European countries in order of their cost-effectiveness. This approach is repeated for successive emission reductions until deposition at or below target loads has been achieved across the map area or until the expenditure ceiling is reached. The RAINS model, on the other hand, has been designed to increase understanding of acidification and other effects (Warren and ApSimon, 1998).

RAINS and ASAM are currently being modified to incorporate primary particulates within their modules. In the immediate future, these models will be able to include primary emissions, calculate the formation of secondary aerosols, assess the abatement measurements that could be implemented**,** calculate the costs of controlling fine particles and, ultimately, assess the health impacts resulting from a certain emission strategy. For primary particulates, a first approximation of the levels of concentration and long-range transport found in Europe has been obtained using the very simple PPM model (ApSimon et al., 2001). Further work in this field to compare results is to be done in conjunction with the final development of the new Eulerian EMEP dispersion model, which will deal with primary particles, secondary inorganic aerosols and organic aerosols. The spatial resolution of the new model will be 50 km * 50 km grid system, instead of the 150 km * 150 km used to date. This new Eulerian EMEP model includes in-cloud oxidation and vertical exchange processes. More refined analysis is expected in the future (EMEP, 1998c).

An initial study done by IIASA (Johansson et al., 2000) on preliminary estimates of PM concentrations in Europe showed that, after adding the estimates from primary, secondary and organic aerosols, the results (with maximums of 30 $\mu g/m^3$ in Central Europe) were comparable with measurements obtained in rural sites. It is also worth mentioning that, according to this study, primary PM contributes to a much lesser extent than secondary PM. This may be explained by the fact that primary emissions from natural sources are not included (e.g. Saharian dust) or because calculations are limited to rural backgrounds and not urban areas where primary PM make a great contribution (e.g. traffic).

Despite all the uncertainties, it is important to bear in mind that, although PM emissions are likely to decline, this will probably not be sufficient to bring annual mean concentrations of PM_{10} below the 20 $\mu g/m^3$ target stipulated by the EC. It seems possible that there will be rural parts of Europe in which this concentration will be exceeded, and consequently the same could be applied, with even more likelihood that it will be exceeded in urban sites. Additionally, when considering episodic conditions rather than annual means, these concentrations are likely to be larger. Measurements and controls will have to be applied in order to avoid this situation, especially at urban sites.

a.19 a.4 Model Intercomparison

In the negotiations in Europe two integrated assessment models have been mainly used: RAINS and ASAM, both of which have been described in detail earlier. Both models have been used to investigate abatement strategies to reduce acidification, eutrophication and human exposure to secondary particulates. RAINS has additionally been used for the assessment of ozone.

RAINS and ASAM use the transboundary fluxes of pollutants provided by EMEP (Barrett and Seland, 1995), the official UNECE or EU emissions and, for EU studies, those of the REFERENCE scenario described by IIASA. Both models also use the critical load maps prepared by RIVM (Posch et al., 1997). Thus the data sets for both models are identical. Both IA models are complementary and can be used together. The fact that there is good agreement between the results of the two models increases the level of confidence that can be placed in the results.

Deposition patterns were compared in detail for all 52 countries for the year 2010 (unconstrained and REFERENCE scenario), and on average there is good agreement (deviation is below 3%). However, there are some differences that can be explained by the fact that RAINS does not state exactly how it has treated the background, marine and unattributable deposition; it is likely therefore that the differences arise from varying assumptions, concerning these contributions to the deposition. RAINS models the marine emissions directly whereas ASAM considers them to be part of the irreducible background. However, the observed differences are within the uncertainties that are expected to be found in the calculation of deposition fields using the EMEP model. Although RAINS and ASAM can use identical critical loads, the area protected will be slightly different in both models because of the slight differences in deposition. ASAM calculates the area protected at a receptor by identifying the two isolines which lie either side of the receptor point when represented in the plane. It then approximates the area protected to the mid-way level. RAINS carries out a more detailed interpolation between isolines. RAINS and ASAM calculate the areas protected in countries by summing the areas protected in the component grid squares.

RAINS calculates its own cost curves for each pollutant for each country in Europe with the different scenarios. ASAM uses IIASA's cost curves and identifies the "Best Economic Environmental pathway" from an initial set of country emissions to a final set of country emission ceilings satisfying environmental constraints. When ASAM uses the RAINS cost curves beginning with the year 2010 with unconstrained emissions and modifies them to obtain new curves starting with the REFERENCE scenario, the results produced are consistent with the RAINS model. However, if ASAM is used to calculate cost curves for 1990 based on the RAINS model, the results will be different because since 1990 emissions have often exceeded the 2010 unconstrained levels, and it would be necessary to re-calculate the new cost curves including the correct energy scenarios for 1990. ASAM can also make use of the SEI cost curves for NOx and SOx. ApSimon et al. (1998) includes an analysis of the differences between the MARACCAS model and RAINS for the calculation of cost curves for NH_3.

The main difference between the two models is that RAINS works by optimising all the costs and benefits to attain a particular target. It delivers an optimum abatement strategy by minimising abatement costs subject to the deposition constraints of reaching the target loads

in each receptor. However, RAINS does not include information about the order in which countries could cut back their emissions. The ASAM model takes the results from here and goes one step further by selecting the optimal pathway towards a particular target by maximising the ratio of benefit to cost. The benefit is normally taken to be the reduction in excess deposition over the target load which occurs when an abatement step is implemented. ASAM can therefore provide information about the emission ceilings that would result if it was decided to spend a fixed amount of money on working towards a particular target rather than attaining it.

In summary, ASAM and RAINS were set up to calculate the optimum solution using the same emission data set, and using identical RAINS cost curves and identical target loads. The deposition patterns calculated by both models are slightly different. A similar exercise including all UNECE countries produced very similar results for SOx, NOx and NH_3 abatement.

There are a number of papers comparing the results obtained by RAINS with the results of other models. Although most of these cannot be considered Integrated Assessment models, there is a need to compare results. For instance, Sowinski, (1995) compares the results from a model of sulphur deposition for Poland with the results from RAINS and concludes that the differences between both models on average deposition are relatively small.

The Hull Acid Rain Model, HARM, (Metcalfe et al., 1995, 1998) is another example. It is a receptor-oriented statistical model for the analysis of acid deposition of SO_2, NO_x, NH_3 and HCl, and, more recently, for particulates. HARM covers acidification and eutrophication of sensitive soil ecosystems. In Whyatt et al. (1995) HARM results are compared with the observed data collected by EMEP, with the results obtained being very similar. The HARM model has also been used in Derwent et al. (1998) together with other models (STOCHEM, TROPOS, URBAN BOX and UKPTM) in order to study the environmental benefits of NO_x control in Northwestern Europe. STOCHEM (Collins et al., 1997) covers the issue of tropospheric ozone and vegetation damage in present day conditions and is explained in more detail elsewhere in this report. Basically, it is a global 3-D Lagrangian air parcel model of the formation, deposition and transport of ozone from NO_x, SO_2, CO, methane and 9 VOCs. It has been used in Europe, and also with emissions from North America and Asia to determine the pattern of ozone changes over Europe and the globe. TROPOS (Derwent, 1996) covers the issue of future tropospheric ozone and vegetation damage. It is a global 2-D Eulerian model of ozone formation, transport and deposition from NO_x, CO, methane and 12 VOCs. It has been used to explain how human activities have already led to a doubling in Northern Hemisphere ozone background levels since pre-industrial times. TROPOS also includes predictions of future concentrations up to the year 2100 using the IS92a scenario of the IPCC (Houghton, 1992). Current expectations from the TROPOS model are that tropospheric ozone baseline concentrations are expected to rise about 3.9 ppb during the May to July growing season across the latitude band of Europe over the decade 2000-2010. URBAN BOX (Derwent et al., 1996) deals with urban air quality; it is a simple box model of a severe wintertime pollution episode in central London and describes the formation of NO_2 during the winter of 1991. UKPTM (Derwent, 1995) deals with episodic peak ozone and human health; it consists of a UK photochemical trajectory model which fully explains the chemistry and transport of NO_x, CO, SO_2, methane and 96 VOCs.

Some of the results obtained using ASAM working with different scenarios can be seen in Warren and ApSimon (2000). It examines the abatement strategies obtained by the ASAM model which are designed to reduce environmental damage to the three different types of target load. The target loads have each been adjusted slightly so that the scenarios represent strategies of an overall cost to UN ECE of each of the scenarios of approximately 10 billion ECU yr^{-1} , which may be within a range useful for policy making.

The Stockholm Environment Institute, SEI-York, has developed an integrated assessment model, the Co-ordinated Abatement Strategy Model (CASM), linking emissions of sulphur and nitrogen oxides with atmospheric transfer, a map of sensitivity to acidic deposition for Europe, and costs of abatement option application in each European country (Bailey, 1996 a,b; Cambridge, 1996).

CASM was developed to generate and evaluate abatement scenarios to support policy development. The model takes information describing atmospheric emissions and their long-range transport, costs of abatement and critical loads, and uses an optimisation procedure to generate cost-effective environmentally targeted strategies.

CASM is also being applied to air pollution from the transport sector. The project aims to examine how emissions of transboundary air pollution from the transport sector can be reduced in Europe through the application of different policy instruments. Initial investigations on sulphur also led to research on critical loads for nitrogen deposition and an on-going project determining the impact of tropospheric ozone on crops and forests.

The CASM model is being used in a project called ‘Accounting and Accreditation of Activities Implemented Jointly’. This project investigates the Framework Convention on Climate Change and the Oslo Protocol (on sulphur emission reductions).

This EU-funded project involves both SEI-York and the SEI-Tallinn office which is collecting data related to joint implementation projects in the Baltic Region for both climate change and sulphur-related activities. SEI-York is analysing joint implementation projects and proposals under the sulphur protocol using case studies in parts of Europe. These activities will lead to sensitivity analysis and methodological guidelines for implementation.

b. North America

a.20 b.1 Acidification and eutrophication

In the US similar studies have been taking place under the NAPAP programme, which has also helped in creating maps of deposition of all pollutants within the US. NAPAP has estimated that emission reductions have resulted in a decrease in air concentrations of SO_2. This decrease is most evident in the Northeast where emissions are most concentrated, but apparently extends across the entire region east of the Mississippi River. Reductions in concentrations of particulate sulphate are also widespread, but are less striking. At a few locations, particulate sulphate concentrations appear to have increased when decreases would have been expected; the reasons for this are not clear, and the data record is too short to provide insight into this apparent inconsistency. For nitric acid vapour in air, regional concentrations show evidence of a widespread reduction similar to that for sulphur species,

although of markedly smaller magnitude and with some variation among sites. Control of NO_x emissions under Title IV of The Clean Air Act) was not required until 1996.

Wet deposition monitoring results clearly and objectively indicate a recent reduction in acid deposition in the eastern United States. In 1995, the concentration of sulphate in precipitation in the East was 10–25% lower than during 1983–1994. This may have been due wholly or in part to the emission reductions. In 1995, dry deposition rates of sulphur at State College, Pennsylvania, decreased to their lowest level since 1986. Deposition rates of nitrogen compounds have slowly increased.

Precipitation data show that widespread declines in sulphate concentrations and acidity (hydrogen ion) accompanied by decreases in such cations as calcium, magnesium, potassium, and sodium have occurred since about 1980. The most significant declines in sulphates and hydrogen ion occurred in 1995. Nitrate and ammonium concentrations showed considerable variability. The acidity (as measured by hydrogen ion) of precipitation may not have declined as much during 1983–1994 due to the simultaneous decline in base cations in precipitation, which act to buffer the acidity, and also to an increase in nitrate. However, 1995 wet deposition data show a substantial drop in acidity (hydrogen ion) and an increase in pH commensurate with the reduction in sulphur concentrations. Deposition of ammonium, which along with nitrate is a significant contributor to nitrogen enrichment to ecosystems via atmospheric deposition, generally increased throughout the United States.

The US Geological Survey (USGS) has been actively studying acid rain for the past 15 years. It has played a key role in establishing and maintaining the only nation-wide network of acid rain - the National Atmospheric Deposition Program/National Trends network (NADP/NTN), and supports monitoring sites all over the US. The information gained from monitoring the chemistry of rain and snow is important for testing the results of pollution control laws on acid rain. The USGS is the lead federal agency for the monitoring of wet atmospheric deposition (chemical constituents deposited from the atmosphere via rain, sleet and snow) in the United States. The USGS atmospheric deposition program provides isopleth maps on deposition and concentrations of SO_4, NO_3, NH_4, Ca, Mg, K, Na, Cl and N.

a.21 b.2 Ozone

Ozone has long been recognised as an important health and ecosystem-related air quality concern in the United States and Canada. Recent health and environmental studies in both countries indicate that adverse effects result from ozone exposure at concentrations much lower than previously thought. The United States has recently revised its ozone air quality standards and Canada is in the process of examining its ozone-related objectives and standards. Both countries are committed to addressing the ozone air quality problem within their own territories.

The Canadian effort to address ozone exceedances began in 1990 with governments co-operating to develop a program to reduce precursor emissions of ozone - nitrogen oxides (NO_x) and volatile organic compounds (VOC) (CCME, 1990). Additionally, a comprehensive scientific assessment has defined the nature and extent of the ozone problem in Canada and established the scientific foundation for management options (Multistakeholder, 1997).

In the United States, 37 eastern states formed the Ozone Transport Assessment Group (OTAG). OTAG has produced substantial documentation on the nature of regional ozone transport and alternative strategies (OTAG, 1997). This led to promulgation of a major new regional regulatory program to reduce the emissions responsible for such transport. The US Environmental Protection Agency (EPA) promulgated this ozone transport rule in 1998 (EPA, 1998).

Recognition of the effects of ozone has been accompanied by considerable monitoring and analyses of the spatial pattern of ozone in the two nations. Large-scale summertime smog episodes occur in the eastern half of both countries, with events that transcend political borders. In Canada, exceedances of the current air quality objective are regional, with areas of concern in southern British Columbia in the West, and throughout the Windsor-Québec City Corridor and the Southern Atlantic Region in the East. A similar pattern of regionally elevated ozone occurs in the United States; nationally, a number of areas in California and the Gulf Coast, as well as numerous locations in the eastern portion of the nation exceed the US standards. Essentially all areas of eastern Canada and most areas of the eastern United States experience high concentrations of ozone.

In North America, in 1991, Canada and the United States signed the Air Quality Agreement, which codified the principle that countries are responsible for the effects of their air pollution on one another. The Agreement initially addressed acid rain, but it also confirmed the commitment of the United States and Canada to consult and develop the means to deal with any transboundary air pollution problems.

As early as 1994, the increasing evidence on regional transport of ozone led to a recognition that ground-level ozone would be an appropriate issue to consider for the Canada-US Air Quality Agreement (AQC, 1994). Members from both countries met in 1995 to draw up a Canada-US Regional Ozone Study Area (ROSA) project. Under this program, the countries initiated regional modelling to evaluate the relative effectiveness of regional controls for ozone pollution in a broad transboundary area in eastern North America. This transboundary work occurred in parallel with the domestic OTAG (US) and NO_x/VOC Science Assessment (Canada) activities. In 1997, the “Commitment to Develop a Joint Plan of Action for Addressing Transboundary Air Pollution" was signed. The commitment was to address jointly shared air pollution problems, with ground-level ozone identified as the next priority. New analyses that extend the regional data and analytical techniques into the Canada-US transboundary region were developed for this report and are summarised below (Dann, 1999, Husar et al., 1999; Schichtel and Husar, 1999).

One of the most comprehensive experiments into the nature of photochemical air pollution occurring over continents in recent years has been the Southern Oxidants Study (SOS). This study drew attention to serious difficulties in understanding the nature of photochemical air pollution, particularly in the Southern USA, and in measures then being adopted to ameliorate the problem. The SOS program, which took place throughout the 1990s, has carried out a series of large-scale co-ordinated experiments using ground-based networks and aircraft supported by a series of modelling studies designed to identify the main factors responsible for the generation of pollution. Most of the study was conducted in the boundary layer. Transfer of the boundary layer pollution to the free troposphere and export of the pollution from the USA to the Atlantic Ocean was investigated in NARE.

NARE was a joint US and European experiment to investigate if the pollution plume of North America could in fact be observed over the North Atlantic, and if the pollution levels were high enough to be significant. Measurements of CO and O_3 provided an extremely useful tool for initial investigations of the anthropogenic impacts on the tropospheric O_3 budget in the North Atlantic. Three sites were operated in Canada at distances progressively further downwind from the eastern US seaboard. The North American pollution plume was readily detectable at all three sites, the furthest being 1500 km downwind from the sources (Parrish et al., 1993). Subsequently, measurements at a site in the Azores located 3000 km downwind from the sources, established that North American pollution enhances O_3 in the central North Atlantic, at least in the spring (Parrish et al., 1998). While these qualitative observations of O_3 and CO transport were important, they also provided the basis for the quantitative assessment of the amount of anthropogenic O_3 transported from North America. Based upon the observed ratio of O_3 to CO and emission inventories of CO, Parrish et al. (1993) concluded that in the summer, O_3 transported from North America exceeded natural O_3 from the stratosphere in the lower troposphere over the North Atlantic.

Also in North America, CICA provides technical support and assistance in evaluating air pollution problems along the México - US Border. CICA is sponsored by EPA's Clean Air Technology Center (CATC) and provides a wide range of technical assistance on: air pollutants and control strategies, pollution prevention and control technology applications, operation and maintenance problems, emission inventory, emission factors, dispersion modelling, ambient monitoring, emission measurement and risk analysis. Ambient air quality data are available for criteria pollutants and are presented in both summary and standard-relevant formats: $PM_{10,}$ lead (Pb), sulphur oxides (SO_x), nitrogen oxides (NO_x), ozone (O_3) and carbon monoxide (CO).

c. Asia

a.22 c.1 Acidification

RAINS Asia calculated sulphur deposition and source receptor matrices in the South East region of Asia by using a model (ATMOS) similar in design to the EMEP model used in Europe to produce the deposition fields for RAINS Europe. In this case the model parameters were chosen as the most appropriate for the region taking into account high levels of dust and tropical conditions. This information was obtained from independent studies.

The results showed that there are very few regions in Asia which are not affected by sulphur deposition. The high sulphur deposition regions closely follow the spatial distribution and density of the emissions. For example, the dense emission regions in eastern and southern China, S. Korea, northern Thailand, and eastern India all show elevated sulphur deposition. The highest annual deposition (~10.5 g S/m^2 yr) occurs around the city of Chongqing in Sichuan province. The strong continental outflow from East Asia is also clearly shown. Sulphur emissions in the latitude band 20° to 40° N result in high sulphur deposition virtually throughout the western Pacific Ocean at these latitudes. Transport and deposition off the eastern coast of India over the Bay of Bengal is shown as is the high sulphur deposition around Malaysia, Singapore and the western parts of Indonesia. The total deposition patterns

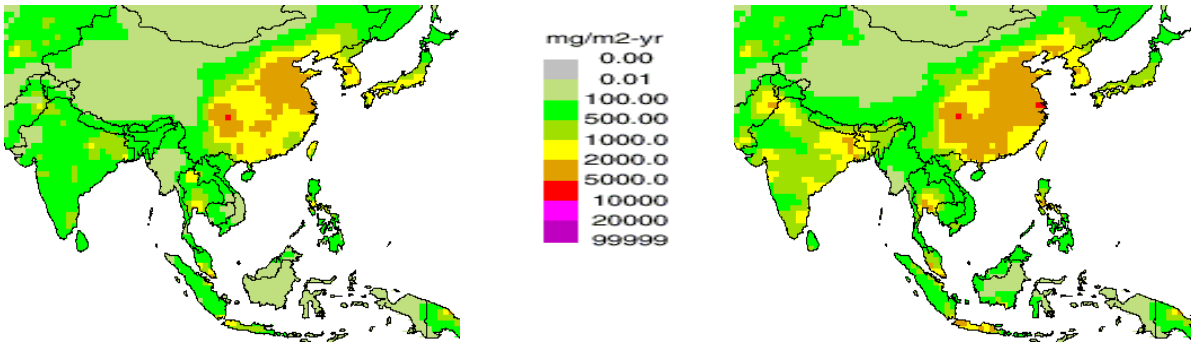
are also heavily influenced by the annual precipitation patterns. High annual precipitation is found to occur in northern India, Nepal, Southeastern China, and Southeast Asia.

Deposition patterns in Asia show a strong seasonal variation. This is due to a combination of factors which include: seasonality of wind and precipitation fields; higher emissions due to domestic heating in the winter months in the northern parts of Asia; and changes in the dry deposition velocities, chemical reaction rates and wet removal rates with latitude and season.

The following figures show the sulphur deposition in Asia calculated by RAINS-ASIA for the years 1995 and 2010 (assuming current legislation) (Source: IIASA)

Sulfur deposition

1995 **2020 with current legislation**



There are many other studies calculating transport and deposition of, for example, sulphur in Asia, including Meiyuan et al. (1995) and Ichikawa et al. (1995). Most of these studies are collected in the Proceedings from the 5th International Conference on Acidic Deposition, in Goteborg, Sweden, June 1995 (ACID REIGN ‘ 95?).

a.23 c.2 Model Intercomparison

The long-range transport of pollutants in Asia is an area of increasing scientific interest and political concern. Long-range transport models will be increasingly used to provide information on the transport emissions from various locations in East Asia in support of science and policy applications. Already, Arndt et al. (1998), Huang et al. (1995) and Ichikawa and Fujita (1995) have investigated source-receptor relationships in East Asia, all

with very different results. The calculated contribution of Chinese sources to Japan's deposition in these studies give markedly different estimates of the role that long-range transport plays in Japan's total deposition. Huang et al. estimated that China accounts for only 3.5% of Japan's total sulphur deposition; they found that over 93% of the sulphur deposited within Japan was from either Japanese anthropogenic or volcanic sources. In contrast, Ichikawa and Fujita (1995) estimated China to be a major source of wet sulphate deposition in Japan, accounting for one-half of the anthropogenic deposition. These variations are due in part to differences in removal rates and chemical conversion rates in the different models. Low removal rates result in greater transport away from source locations and thus higher transboundary pollution. There is a great need to conduct model intercomparison studies to better understand how to model long-range transport in East Asia.

Previous work on comparing acid deposition models applied in and around Japan has included a joint study comparing CRIEPI (Ichikawa and Fujita, 1995) and ATMOS (Arndt and Carmichael, 1995) trajectory models with Eulerian results (i.e. the STEM model, Carmichael et al., 1991); Phadnis and Carmichael (1998) have reported these results. The most recent intercomparison study has been between CRIEPI and the National Taiwan University RADM/MM5 models, conducted under a joint project of CRIEPI and the Taiwan Power Company (Hayami et al., 1999). This study utilised the same meteorological data and emissions and covered three episodes in 1993. The objectives of the study were to compare model runs with different meteorological data (but the same period - e.g. objectively analysed winds vs. MM5) and trajectory and Eulerian models run with the same (MM5) meteorological data. Comparisons were made with SO_2 and sulphate concentration and deposition fields for East Asia.

A Workshop on Transport of Air Pollutants in Asia was held at the International Institute for Applied Systems Analysis (IIASA, 1998), when issues related to the modelling of long range transport in Asia were discussed. The attendees recognised that, in order to help improve the use of models in science and policy analyses in Asia, it was necessary to have a better understanding of model performance and uncertainties. The group initiated a model intercomparison exercise to be carried out as part of the joint collaborative studies involving the CRIEPI/IIASA and RAINS-Asia projects. An overview of this study is presented in Carmichael et al., 1998)

In general the observations fall within the range of the model predictions, with the exception being sulphur-wet deposition at sites like Taichung. Furthermore, all the models agreed in the observed increase in sulphur deposition (by about one order of magnitude) over east China compared to Japan.

The model calculating sulphur deposition was further studied by comparing the sulphur deposition quantities and the contributions due to each process (i.e. dry/wet as SO_2 and sulphate) at various target regions. Variations in predicted sulphur deposition range from ~50% in South Korea and Eastern China, to 400% in Central China. The predictions are very similar in terms of the relative importance of the various pathways. Dry deposition as SO_2 and wet deposition as sulphate are the two dominant terms. In fact, the models are very robust in predicting the wet to total sulphur deposition ratio. All models predicted this ratio to be between 0.6 and 0.7 over Japan and between 0.35 and 0.5 over Eastern China.

All the models show the same general features, with the high source areas clearly located within the subdomains. However the models do differ in terms of the magnitudes of the peak values, and the structure of the horizontal and vertical distributions. For example, in Southern Korea, some models showed much stronger horizontal and weaker vertical gradients than others. It appears that model differences are less dependent on model framework (Lagrangian vs. Eulerian), than on the number of vertical model layers, and the numerical algorithms (i.e. diffusive characteristics) and assumptions (e.g. whether horizontal diffusion was included explicitly or not) used for horizontal and vertical transport.

The results were not found to differ very substantially in terms of concentrations and depositions, although the chemical conversion and scavenging rates differ by at least a factor of 2. At this stage the uncertainty in emission inventory, and in the driving meteorology, is much larger than the uncertainty in the model parameters. As the combined results from the different models and tasks have shown, it is in fact difficult to adjust the parameters of these models to cover the broad spectrum of conditions occurring within the domain in different seasons. This problem is exacerbated by the objective difficulties in collecting coherent sets of long-term measurements over the whole area.

d. Arctic

a.24 d.1 Acidification, eutrophication, heavy metals and POPs

The AMAP programme for the Arctic also studies the long-range transport and deposition of pollutants in that region. Under the AMAP project, concentrations and deposition of acidifying pollutants, heavy metals and POPs have been calculated; further work is needed to be able to reach firm conclusions. Although there is evidence that the problem in the Arctic is of a transboundary nature, more investigation is needed, especially of emissions from the so-called developing world (South America, Africa and Asia) and of the impact of the atmospheric transport of these pollutants.

e. Elsewhere

There have been a number of independent studies calculating the long-range transport of pollutant in different parts of the globe. For instance a regional-scale Eulerian air pollution model was applied to the analysis of the long-range transport (LRT) of air pollution in the China, Korea, and Japan corridor of the Pacific Rim. The transport, chemical transformation, and dry deposition during LRT events typical of spring months are analysed; the long-range transport of sulphur dioxide, ozone, and nitric acid are shown to be significant (Kotamarthi et al., 1990). A study by Bridgman (1995) looked at the potential impacts of the long-range transport of pollutants in the Southwest Pacific. Recent studies from South Africa suggest that emissions from bushfires and other sources in Australia could have a significant effect on atmospheric chemistry, and especially on the levels of tropospheric ozone in the atmosphere over the Southwest Pacific region. Following a dust episode in Hong Kong in 1996 (Zheng et al, 1999), aerosol samples were collected and analysed, with the resulting data indicating the transport of mineral aerosols from northern China.

Other similar studies are the NASA GTE Pacific Exploratory Missions (PEM) and the East Asia/North Pacific Regional Study (APARE). The PEM West Missions characterised in detail the chemical composition of airmasses and the meteorological factors that controlled their distribution over the Northwestern Pacific (e.g. Gregory et al., 1997; Talbot et al., 1997; Blake et al.,1997). The Industrial Pollution and Biomass-burning over the Tropical Pacific (PEM-WEST-B) observed extensive biomass burning transported 10,000 km or more from fires in South America and southern Africa. The PEM-Tropics measurements over the tropical North Pacific showed relatively high ozone concentrations and revealed a complex mix of combustion influences. A major component was long-range transport from the Eurasian continent which extended over the full longitudinal extent of the Pacific and appeared to include major pollution contributions from both Europe and Asia. Long-range transport from western North America at low altitudes around the Pacific High and into the trade wind circulation was found to make a significant contribution to pollution levels in the tropical boundary layer over the north Pacific. The Indian Ocean Experiment (INDOEX) was a multiplatform measurement campaign, performed during the dry monsoon from January-March. During this season a persistent northeasterly flow carries pollutants from India and the southeastern Asian region toward the equator over the Indian Ocean. The measurements revealed that large amounts of carbon monoxide and aerosols, both from biomass burning and fossil fuel related emissions, spread over the entire northern Indian Ocean basin.

There have been a number of independent studies, most of which are collected in the Proceedings from the 5th International Conference on Acidic Deposition, in Goteborg, Sweden, June 1995 (ACID REIGN ‘ 95?).

The Air Pollution Information Network (APIN) is one of many activities of the Stockholm Environment Institute (SEI) program on Atmospheric Environment Issues in Developing Countries, a long-term internationally funded effort to promote new co-operation on trans-border environmental issues between developed and developing countries. APIN links science and research to policy by developing regional information databases mainly in Latin America, Africa and Asia. Their website (http://www.york.ac.uk/inst/sei/APIN/welcome.html) has all the available databases. The aim of this project is to promote communication between the different experts through the worldwide web. Another initiative to facilitate the development of action plans, strategies and policies for pollution prevention and control has been developed by SIDA, the Swedish International Development Co-operation Agency, which is funding a Programme on Atmospheric Environment Issues in Developing Countries. This Programme is also co-ordinated by the Stockholm Environment Institute (SEI).

3.2 Global Studies

a. Acidification and eutrophication

On a global basis, the RIVM/UNEP report has estimated deposition based on the STOCHEM model developed by the Meteorological Office (UK) (Stevenson et al. 1998). This model has been used to assess S and N deposition fluxes on a 5° x 5° resolution on the basis of the 1992 and 2015 emissions of SO_2 , NO_x and NH_3 as described in the previous sections (Collins et al. 1997; Stevenson et al. 1998). The model calculates the deposition and surface concentration of several tropospheric air pollutants on a 5° x 5° grid basis for the world as a whole. The impetus for calculations with this model are emissions from fuel combustion, biomasss

burning and emissions from agriculture. Other model estimates are available, such as 10° x10° resolution deposition fields simulated with the MOGUNTIA model for NH_x in Dentener and Crutzen (1994), Holland et al. (1997) and Lelieveld et al. (1998) for NO_x.

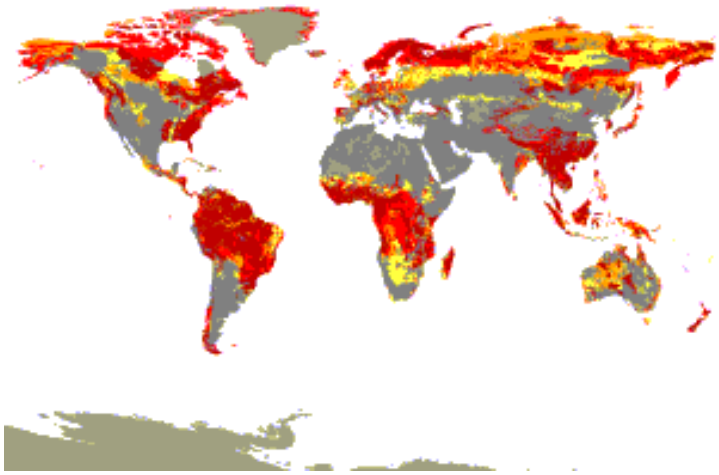
With this resolution the long-range transport of S and N compounds can be represented reasonably well. The deposition data for both S and N were redrawn from the original 5° x 5° to a 1° x 1° resolution using a filter smoothing the spatial patterns. It is not possible to describe the short-range local dry deposition of gases, in particular ammonia, using the STOCHEM model. For sulphur and nitrogen oxides, this process is much less important. To account for more short range processes, 1° x 1° resolution emission fields for NH_3 were used to estimate the dry deposition of NH_3 close to the sources. The fraction of the total emission that is dry-deposited within a few km from the source depends on many factors, including the height of the source and the surface roughness (Asman 1998), and the compensation concentration (Conrad and Dentener 1999). Most terrestrial sources are close to the surface, giving a fraction of 0.4-0.6 of re-deposition of the emitted NH_3 within 2 km of the source for a neutral atmosphere (Asman 1998). Re-deposition may amount to about 0.4 for a roughness length of 0.25 m (coniferous forest) and 0.6 for roughness lengths in the order of 1.0 m (deciduous forest). As the ecosystems considered are natural with more pronounced roughness variation than agricultural fields, the overall fraction of re-deposition of the emissions is assumed to be 0.5. This fraction was used to modify the 1° x 1° deposition fields with the 1° x 1° emission inventory of Bouwman et al. (1997). For certain vegetation types this may underestimate dry-deposition fluxes, while for ecosystems with low roughness lengths this fraction may be an overestimate. Another way to add more spatial variation in deposition fluxes may be by presenting differences in vegetation types to estimate differences in compensation points of canopies for describing deposition fluxes. Since describing this effect for the spatial resolution of 0.5° of the vegetation/land cover database would introduce many uncertainties - for example, by not describing meteorological variability and other sub-grid effects - the deposition fluxes in this study were not corrected for differences in vegetation.

Comparison of the STOCHEM deposition fields for 1992 with (regional) assessments showed a good correlation with EMEP estimates of N and sulphur deposition in Europe (Tuovinen 1994), MOGUNTIA model results for N deposition at the global scale (Dentener and Crutzen 1994; Holland et al. 1997; Lelieveld et al. 1998), and RAINS Asia information on S deposition (Foell et al. 1995).

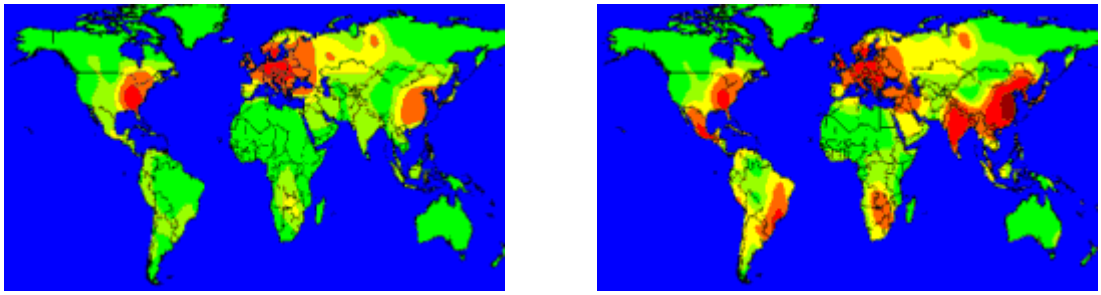
For 1992, the calculated deposition onto global land areas shows that the highest mean S deposition rates occur in Eastern Europe, followed by OECD Europe and USA. The highest maximum S deposition rates occur in Eastern Europe and OECD Europe, and somewhat smaller fluxes in North America and the former USSR. The highest mean regional N deposition rate occurs in Eastern Europe, followed by South Asia and OECD Europe. Other regions with somewhat lower deposition rates are Japan and East Asia. The highest maximum N deposition rates occur in East and South Asia, with somewhat lower maximum deposition rates in Western and Eastern Europe, North America, South East Asia, Western and Eastern Africa and Japan. While nitrogen dominates the acid deposition in most parts of the world, sulphur dominates the acid inputs in regions close to the industrialised regions with high S emissions.

For Europe and South East Asia the global map shows a good correlation with results of regional acidification assessments (e.g. Posch et al. 1997; Foell et al. 1995), despite differences in the scale of calculations. In general, the results of this assessment agree with other global studies such as Rodhe et al. (1988) and Kuylenstierna et al. (1998). However, most of them only considered S deposition. When N inputs are included as a cause of acidification, as in the RIVM/UNEP study, it can be seen that the potentially affected areas are significantly larger and further away from the highly industrialised areas, when compared to previous global studies considering S deposition alone. Hence, N deposition may form an important contribution to acidification.

The following figure shows the global distribution of the five classes of sensitivity to acid deposition. In it the most affected areas are the darkest areas (source: RIVM-SEI (Cinderby et al., 1998)).



According to the CRP scenario, the total global S deposition onto terrestrial surfaces does not alter between 1990 and 2015, although there are considerable regional differences. Between 1990 and 2015, deposition rates in Canada, USA, Western and Eastern Europe and the Middle East are projected to decrease, while in other global regions they are projected to increase. The global terrestrial deposition for N increases as a result of increases in all world regions. These N deposition estimates exclude short-range dry deposition of ammonia.

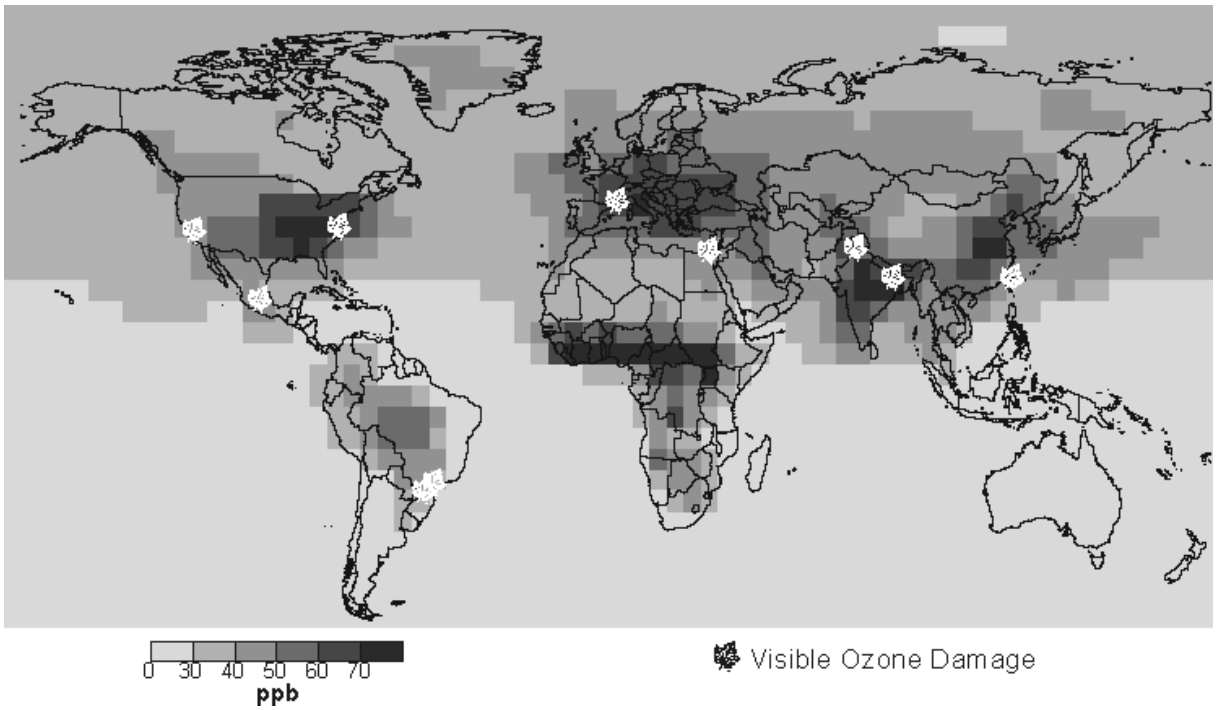


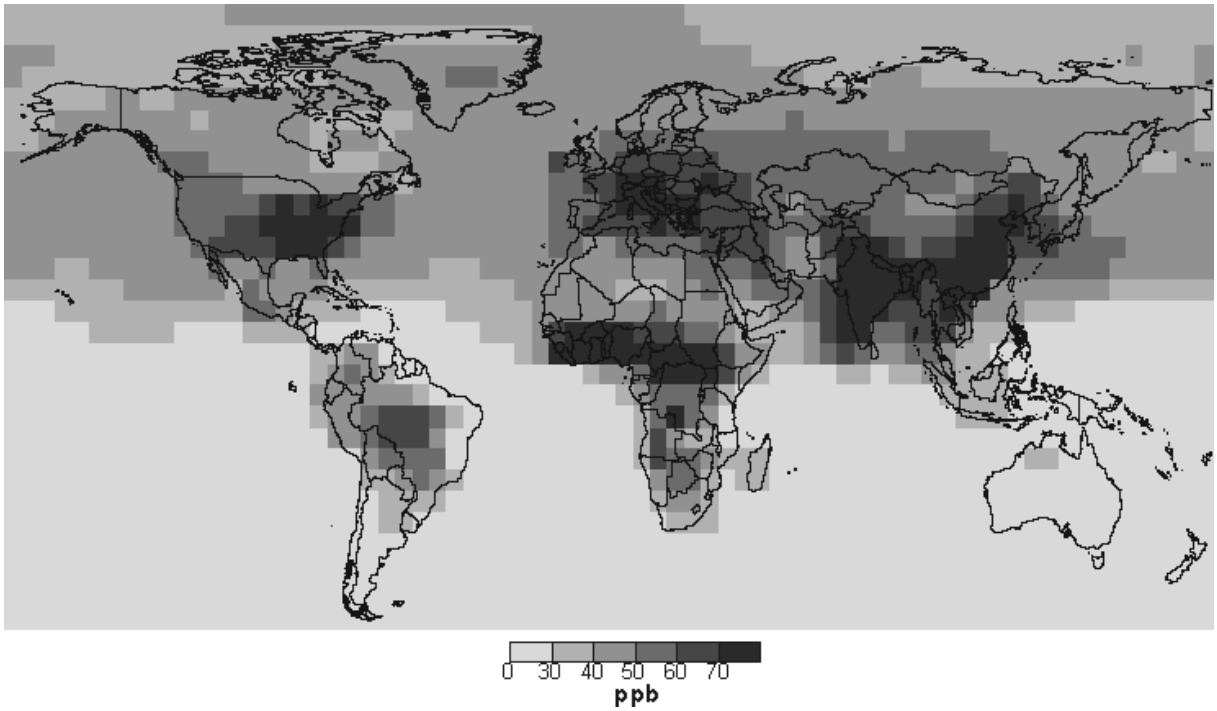
These maps (source SEI: Cinderby et al., 1998) show the estimates for sulphur deposition for the years 1985 and 2050.

b. Ozone

Models have been developed to attempt to predict both current and future global ozone concentrations (e.g. STOCHEM global ozone model developed by Collins et al., 2000). These models show that, assuming a "business as usual" scenario (i.e. with no attempts to control the precursor emissions of ozone pollution), ozone concentrations are set to increase dramatically in the future both in terms of higher concentrations and in the area/regions covered by these high concentrations.

The following maps show the mean maximum growing season O_3 concentrations for 1990 and 2030, respectively, and areas where site-specific visible O_3 damage to vegetation has been observed. Data produced by the STOCHEM global ozone model. (Source: UK Met. Office)





EUROTRAC, the European Experiment on Transport and Transformation of Environmentally Relevant Trace Constituents in the Troposphere over Europe, was a European Scientific research project within the EUREKA framework. The objective of EUROTRAC was to increase the scientific knowledge of the impact of human activities on the troposphere over Europe. It focused on the scientific aspects of two of the major air pollution problems occurring on a European scale: the chemistry and transport of photo-oxidants (ozone) and the chemistry, transport and deposition of acidifying substances. GLOMAC (Global Modelling of Atmospheric Chemistry) is a sub-project of EUROTRAC, and its basic aim is to develop and apply 3-D models of the global troposphere and lower stratosphere for simulation of transport, transformation and removal of chemical species relevant to the occurrence of ozone in the troposphere and to the dispersion and deposition of acidifying pollutants. One of the tools used within the GLOMAC project is MOGUNTIA (Crutzen and Zimmermann, 1991), a relatively simple meteorological model based on monthly mean climatological data in combination with a more complex chemistry scheme. MOGUNTIA has been extensively tested and refined to apply to a variety of situations. Despite its obvious limitations (poor spatial and temporal resolution) it has proven to be very useful for first order estimates of global distributions. MOGUNTIA was originally used to look at historical trends in global O_3 concentrations. It confirmed that the highest O_3 production occurs between 30 and 60 degrees N with O_3 destruction occurring over the remote tropical oceans. The model indicates an average lifetime of tropospheric ozone in the northern hemisphere to be about a month compared to 1 to 2 days for NO_x. The lifetime of ozone actually varies from a few minutes in urban areas within the boundary layer to several days in a clean boundary layer, and to many months in the upper free troposphere which has low temperatures and concentrations (Ebel et al., 1997). The long lifetime of O_3 has implications for its transport and distribution in the northern hemisphere. North America contributes about 30% of man-made NO_x emissions to the northern hemisphere. This NO_x, together with the direct export of O_3, is estimated to add a considerable amount of O_3 per year to the northern hemisphere, which raises the question of a transatlantic influence on the level of photochemical oxidants in Europe. (Ebel et al, 1997).

For instance, measurements made in the Canary Islands show high O_3 concentrations persist until August in air masses from the northern part of the North Atlantic. At most remote sites in the northern hemisphere, O_3 concentrations have usually fallen from their highest value in August, so these high values are probably the result of the export of both O_3 and its precursors from the North American Continent into the free troposphere over the Atlantic (Hov, 1997)

The MOGUNTIA model has also been made available to other groups outside GLOMAC. For instance, it has been used to simulate the tropospheric portion of the atmospheric sulphur cycle (Langner et al., 1992) and to simulate the global distribution of elemental mercury and divalent mercury (Gallardo and Rodhe, 1999).

The Stockholm Environment Institute, SEI, has been dealing with atmospheric environment issues in Europe and other developing and developed countries for a number of years. The projects are divided into modelling and mapping studies and joint implementation projects in Europe, and atmospheric environment issues in developing countries. This latter area includes issues related to regional air pollution, ozone depleting substances and global climate change.

Asia and Europe are the main regions in which projects are being carried out under the Atmospheric Environment Programme. The regional air pollution projects also span Africa and Latin America and it is considered important to maintain this more global approach.

Earlier work led to a project looking into regional air pollution in all developing country regions together with collaborators in Stockholm University and SMHI (Swedish Meteorological and Hydrological Institute). In 1997 this project expanded considerably with the setting up of regional Air Pollution Impact Networks (APIN) in Africa, Latin America and Asia. The work culminated in the preparation of a background document in 1998 which will inform three policy dialogues in each of the regions. In the background document the findings on emissions, atmospheric transfer and deposition, and sensitivity and risk, together with scenarios for 2025 and 2050, are developed.

The networking will continue to build the Air Pollution Impact Networks in each region. This project, along with other national and international efforts, aims to encourage nations to develop action plans, policies and steps to abate or avoid pollution.

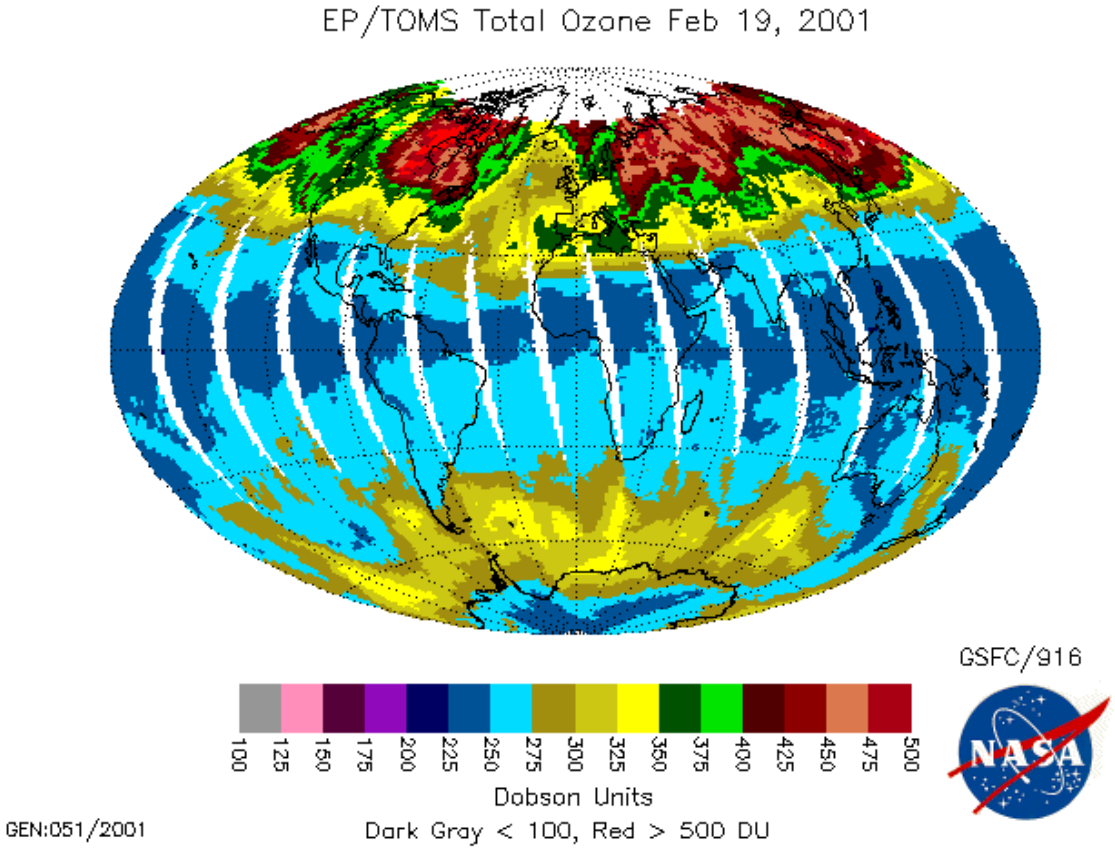
The project includes support to developing country government agencies responsible for policies for emission reductions of substances which deplete the stratospheric ozone layer (ozone depleting substances or ODS) (UNEP and SEI, 1996 a,b). It also includes projects in developing countries relating to climate. SEI has also carried out two studies examining the adaptation of rural communities in India to climate change (Deshinkar, 1997 a,b).

Global monitoring of pollutants is also undertaken through the Total Ozone Mapping Spectrometer, launched onboard an Earth Probe Satellite (TOMS/EP), in July 1996. This continues NASA's long term daily mapping of the global distribution of the Earth's atmospheric ozone. It measures ozone indirectly by monitoring ultraviolet light and has mapped in detail the Antarctic "ozone hole", which forms from September through November of each year, and the distribution of ozone over the globe. In addition to ozone, TOMS measures sulphur dioxide and ash released in volcanic eruptions as well as aerosol particles (airborne microscopic dust/smoke), e.g. those blowing out to sea from North Africa. The data

from TOMS have been increasingly used to understand the behaviour of this material within the atmosphere. The TOMS is the first tool to allow observation of aerosols as the particles cross the land/sea boundary. Using these data it is possible to observe a wide range of phenomena such as desert dust storms, forest fires and biomass burning.

TOMS is part of NASA's Mission to Planet Earth a long term, co-ordinated research effort to study the Earth as a global environmental system. Using the unique perspective available from space, NASA will observe, monitor and assess large-scale environmental processes, focusing on climate change. MTPE satellite data, complemented by aircraft and ground data, will enable natural environmental changes to be better understood and distinguished from human induced changes. MTPE data will be available to researchers worldwide.

The following figure shows an image from TOMS showing the distribution of ozone around the globe (source: NASA).



4. ABATEMENT METHODS AND COST

There are a number of technologies that can control emissions of sulphur and nitrogen from power production. Pre-combustion technologies remove sulphur prior to combustion by coal or oil cleaning. Sulphur and nitrogen can also be removed during combustion, using in-furnace limestone injection, coal briquettes for domestic combustion or fluidized bed combustion. Post combustion methods remove nitrogen or sulphur from flue gases.

In Europe, the US and most of the Western world the research on abatement measures for major pollutants is considered well developed. The same types of technologies apply and with similar costs and efficiencies. For developing nations, the situation is not so encouraging and in Asia it varies from country to country. For example, by 1985 Japan had already abated much of its sulphur emissions through a combination of different control technologies. This represents a considerable improvement on the level of unabated emission. A clear improvement can be seen by comparing the distribution of emissions under this degree of abatement to the unabated emissions for 2025 .

For developing countries, it is possible to improve their well-being without increasing pollution - that is, to separate economic growth from primary energy consumption by investing in more efficient supply frameworks, improving energy efficiency amongst end-users, and substituting renewable energy technologies for fossil fuels. Air pollution may be prevented by the use of alternative energy sources. Some renewable technologies such as wind energy, small-scale hydro and conversion of waste to energy are already competitive with conventional sources of supply.

The key to future development lies in providing the services which people need by using the most efficient technologies, and consuming the lowest possible level of material resources. These may be promoted using the most appropriate policy framework.

Although currently expensive to operate, other technologies have considerable long-term potential. One of the most significant of these is solar photovoltaics involving the direct conversion of sunlight to energy. Although currently only economical in niche markets the costs of module production have been falling for two decades and are set to go on falling as conversion efficiencies rise. Increasing interest both from national governments and multinational companies suggests that the future of energy supply will look very different in the future.

Reducing acid emissions by preventive options for pollution control (improved efficiency and switching to other energy sources) are generally considered advantageous over control options. Control options are costly to implement and give rise to environmental impacts elsewhere in the economy. By contrast, preventive options aim to reduce emissions everywhere by lowering the energy and material throughput of conversion processes generally. They also reduce other pollutants, most notably carbon dioxide from fossil fuel combustion. Indeed, environmental protection through increased efficiency and other preventive options does not necessarily cost money; it can save money. The truth of this remark is borne out by an increasing emphasis on the concepts of pollution prevention, waste minimization and clean technology worldwide.

The main policy frameworks available to implement acid emission prevention and control options are regulatory measures and market-based instruments. Well-designed legislation is generally effective in ensuring that environmental standards are set and there is evidence that appropriate legislation can promote technological improvement. It is argued that market-based instruments are more flexible and cost effective, but their effectiveness depends heavily on institutional factors. Essentially any comprehensive environmental policy framework is likely to use both regulatory and market-based mechanisms.

In order to complete an integrated assessment study, an economic assessment is also essential. The integrated assessment approach in Europe has used the calculation of effects and costs of emission reduction strategies as a very powerful tool. RAINS-Europe calculates cost curves for most pollutants. The optimisation module within RAINS uses information on emission control costs together with a description of pollutant chemistry and transport based on EMEP to determine the least-cost allocation of emission control measures for achieving specified environmental targets. As a result, the optimisation module can identify, within the constraints imposed by the modelling framework, the (country-specific) cost-effective abatement level for the pollutants under consideration and the costs of the implied measures.

RAINS identifies for each of the emission source categories considered in the model, a limited list of characteristic emission control options. For each of these measures, the model extrapolates the current operating experience to future years, taking into account the most important country- and situation-specific circumstances modifying the applicability and costs of the techniques. A detailed description of the methodology adopted to estimate emission control costs can be found in Amann (1990), Cofala et al. (1997), Klimont et al. (1998) and Klaasen (1991). The databases on emission control costs have been constructed based on the actual operating experience of various emission control options documented in several national and international studies. The main references are the proceedings of various UNECE Seminars on Emission Control Technologies (UNECE 1996b, UNECE 1997c), the Technical Annexes to the Second Sulphur Protocol (UNECE 1994a) and other documentation (Schärer, 1993; OECD, 1993; Takeshita, 1995; Rentz et al. 1996). Data for mobile sources are based on material developed within the EU's Auto-Oil Programme (European Commission, 1996). Country-specific information has been extracted from relevant national and international statistics (ILO, 1995; IMF, 1995; UNECE, 1995, 1996a) and was provided by national experts.

In the US, the NAPAP project has used a similar methodology to calculate the cost of abatement to reduce acidification. The Acid Deposition Control Program is being implemented in two phases and has two major goals: reduction of total SO_2 emissions by 10 million tons below 1980 levels by 2010, and reduction of NO_x emissions from coal-fired boilers that will contribute to the overall target of a 2-million-ton reduction below 1980 levels by 2000. The estimation of the costs of this can be compared with other projects and extrapolated to other regions.

The USEPA database contains much information on abatement technologies and costs. The Clean Air Technology Center (CATC) serves as a resource on all areas of emerging and existing air pollution prevention and control technologies, and provides public access to data and information on their use, effectiveness and cost. All the information can be downloaded from their web site in the form of air pollution technology fact sheets (FS) and technical bulletins (TB). It contains information on all sorts of abatement technologies for the main pollutants (e.g. cyclones, scrubbers, catalytic incinerators, fabric filters, electrostatic precipitators, etc.) as well as advice on which are the best control technologies that could be applied to a specific situation. The Economics and Cost Analysis Support (ECAS) contains the documents developed by the Innovative Strategies and Economics Group (ISEG). These documents include analyses of costs, benefits, and economic and regulatory impacts of air quality management strategies and programs, as well as regulations developed by the Office of Air Quality Planning and Standards (OAQPS). All this information can be downloaded

from the web in the form of the OAQPS Control Cost Manual, 'COST-AIR' Air Pollution Control Cost Spreadsheets for implementing the manual and Escalation Indices for Air Pollution Control Costs. Potentially all this information could be extrapolated to the globe, taking into account economic and social differences.

For the RAINS-Asia study, the technology characteristics that have been used to date are largely based on European and North American experience. As the project progresses, for example to assessing costs and emissions under future scenarios, it is important that RAINS-ASIA uses appropriate technologies for the Asian context and also appropriate cost, performance, and application data for these technologies. An Asian technology characterisation database is needed that could be used within the model and also for stand-alone analyses. At the very least, this database would need to include low-cost technologies that are not typically analysed in the West (e.g. coal briquetting, CFBC, and wet particle scrubbers), low-cost adaptations of western technology, and appropriate technologies for Asian energy resources (Thai lignite, high-ash Indian coals, etc). Costs should also reflect regional costs for labour and materials, as appropriate. The database should include both energy production and emission control technologies.

The Protocol to Abate Acidification, Eutrophication and Ground Level Ozone in Europe has been prepared under the UN/ECE CLRTAP. Negotiations focused mainly on the balance between the extent of improvement in certain key environmental quality and health indicators for acidification, eutrophication and ground level ozone, and associated costs of abatement for the pollutants SO_2, NO_x, VOCs and NH_3. The Task Force on Economic Aspects of Abatement Strategies (TFEAAS) has initiated a series of additional studies to extend the assessment of the benefits of pollution abatement. AEAT has carried out a study (Holland et al, 1999) to quantify the benefits of abatement in terms of both impacts and their economic value. This explicit valuation allowed the estimated costs of abatement to be compared directly with benefits in a cost-benefit analysis (CBA).

The AEAT study was based on the RAINS determination of the least-cost combinations of measures for achieving lower emissions for the pollutants under consideration for each country/region for different scenarios (Amann et al., 1999). Costs and emissions are taken from the results of the RAINS model; dispersion calculations are based on EMEP, and databases on stock at risk (people, ecosystems, etc.) were supplied by the Coordination Center for Effects at RIVM; exposure–response functions and valuation data have been taken from a number of sources. This information is then fed into ALPHA (Atmospheric Long range Pollution Health / environment Assessment) Model, which calculates data on stock-at-risk across Europe, pollutant dispersion for SO_2, NO_x, NH_3 and associated secondary pollutants (except ozone), dose-response functions and valuation of the data. ALPHA has as a result country specific estimates of the benefits of pollution abatement which can then be used to compare costs and benefits in a structured sensitivity analysis. Effects on health, materials, visibility, crops, forests and other ecosystems were included in this study.

Based on the principal set of assumptions followed in the study and bearing in mind uncertainties, the most important impacts in the benefits analysis were those on human health and crops. Effects on the agricultural sector are complicated, as sulphur and nitrogen depositions have the capacity to improve crop growth, whilst ozone will reduce it. Overall, the negative ozone effect substantially outweighs the benefits of S and N fertilisation. Effects

on timber productivity and materials were negligible in comparison, whilst those on ecosystems were unquantified, beyond reiterating some of the results on critical loads exceedance provided by Amann et al (1999). Overall the list of benefits quantified here are likely to exceed the costs of implementing all of the scenarios considered by a factor of between two and three. A number of effects, including those on ecosystems, remained largely outside the analysis because of limitations on the availability of data – these would add to the quantified benefits.

Additionally, AEAT presented in the TFEAAS a project (Holland et al, 1999) on the application of economic instruments, as an alternative to other measures, for the abatement of NO_x, SO_2, VOCs and ammonia. The implementation of these instruments would help reduce the overall cost of implementation and can, in principle, bring about a full internalisation of the environmental costs, thus leading to the optimal level of pollution control. The further the emissions in a country or a sector are to be reduced, the higher the marginal cost of abatement will tend to be and the more important cost-effective implementation becomes. A common feature of economic instruments is that they leave some freedom of choice to the producers and consumers concerned. This enables them to exploit cheap abatement options that are valuable to them and provides an incentive to develop less costly measures of emission control.

Economic instruments have been defined by the OECD (1989; quoted in OXERA 1997) as: "instruments that affect costs and benefits of alternative actions open to economic agents, with the effect of influencing behaviour in a way that is favourable to the environment".

Some of these instruments - analysed by AEA, and the impact they have had in several countries compared - are

- ***emission charges*** (payment required in relation to the amount emitted of a given pollutant or the characteristics of the pollutant);
- ***product charges*** (substitutes for emission charges, where the level of pollution resulting from a particular activity can better be quantified by the amount of a product that is used in or results from the activity);
- ***tradeable permits*** (instead of determining the emission limits for a specific plant, a sum of emissions for a specific area or source category is defined and transferable rights (permits) to emit are distributed among enterprises);
- ***subsidies*** (low-interest loans, accelerated write-off allowances, cash grants for investments in pollution equipment, research and development);
- ***voluntary agreements or covenants*** (between industry and the government; both parties to the agreement specify targets such as emission levels or the introduction of abatement technology over a particular time horizon. Industry agrees to be bound by the agreement and plan of action. Government agrees to desist from revising the targets within the period of the agreement);
- ***process charges*** (special case of an emission charge, where, the charge is based on the use of a specific production process);
- ***deposit-refund schemes*** (a surcharge is attached to the price of a potentially polluting product, but is refunded when pollution is avoided by returning these products or their residuals to a collection system).

The Acid Rain Division of the US EPA has carried out, under the NAPAP assessment, a study similar to that done by AEA in assessing the Human Health Benefits from Sulphate Reduction Under Title IV of the 1990 Clean Air Act Amendments (EPA, 1995). This assessment also relies on available economic information for estimates of willingness to pay (WTP) for changes in risks of specific health effects. Results were obtained for the 31-state eastern United States area and also for Ontario and Quebec.

The estimated benefits for Canada occur primarily in the Windsor-Quebec corridor, where the greatest proportion of the Canadian population likely to be affected by the transport of SO_2 emissions from the eastern United States is located. The estimates for Canada do not increase substantially from 1997 to 2010 presumably because the upwind locations in the United States that affect this area see their greatest reduction in SO_2 emissions in the first phase of the Title IV program.

Economic assessment of the benefits of abating acid pollutants can play an important role in developing national and international strategies to reduce acidification and other environmental stresses. This is precisely the aim of integrated assessment studies: calculating cost-effective strategies for attaining target loads for deposition according to the data provided. ApSimon, Pearce et al., (1997) provide a summary of what is known in Europe on acid rain damage and the economic costs. They quantify the different impacts of acid rain in Europe on forests, freshwaters, biodiversity, crops, buildings and materials, health, visibility, etc and analyse the economic consequences as well as the uncertainties.

III. Uncertainties and constraints

In the course of this review a large number of detailed uncertainties affecting IA (and in particular its potential global application) have been identified. These are classified and listed below, as a checklist for future reference. At this early stage there is no attempt to scale them or assess their implications. A preliminary overview of the more general issues is however included as a separate paper.

1. Emissions of acidifying and eutrophying pollutants

Uncertainties in emissions are discussed in Olivier et al. (1998), Lee et al. (1997) and Bouwman et al. (1997). These articles indicate that uncertainties vary strongly from one region to another, and are associated mainly with lack of measurement data, scarcity of data (particularly on agricultural management), lack of information on spatial and temporal distribution of fluxes for diffuse sources such as soils and aquatic systems, and re-absorption of N gases by canopies in terrestrial ecosystems.

More specifically, there is a need for development of better validated emission estimates for nitrogen oxides and ammonia. One reason for the uncertainties in ammonia emissions is that, for most countries, ammonia emissions are estimated, not measured. Moreover, emissions of ammonia show a large spatial and temporal variability; transport models of ammonia and ammonium utilise larger grid scales and the temporal variability of ammonia emissions is not accounted for in such models. Most models of ammonia chemistry and transport are highly simplified and parameterised and may therefore produce results that, even if correct, are correct for the wrong reason. A further reason for the uncertainty is that very few measurements of gas phase ammonia and particulate ammonium are available.

Since, in the near future, data is unlikely to become available to improve current emission inventories, one approach would be to validate emission fields from those countries where they do exist, possibly using forward and inverse atmospheric chemistry transport models. Applying various scaling approaches can also reduce uncertainties. Examples of such approaches include the delineation of functional types in ecosystems and the use of flux models, as discussed by Bouwman et al. (1999). For most gases, flux measurements are required according to measurement strategies based on the functional types.

The emission scenarios used in the majority of studies are most detailed for Europe and the United States, where existing policies have been integrated into the emission scenarios. For other regions, the emission scenarios are simple extrapolations, not based on existing plans and policies.

2. Deposition of acidifying and eutrophying pollutants

Major uncertainties are found in the low resolution of deposition fields, which are used in combination with high-resolution vegetation errors in emission fields and the atmospheric chemistry transport models used.

For N deposition, processes such as leaching, immobilisation and denitrification play an important role. In the majority of studies, relatively simple equations have been used to incorporate these processes into the analysis. In addition, the net uptake of N by plants was assumed to be negligible. A simple model describing these processes would be a major improvement.

A further uncertainty is the deposition of base cations, where an assessment of soil dust deposition has generally been used. By assuming a Ca content of 20 percent for all soil dust particles irrespective of their origin, the estimates are consistent with a number of point measurements in Europe and Asia. However, soil dust is not the only source of Ca deposition, and soil dust also contains other base cations and weatherable minerals. In addition, maximum Ca content in soils is less than 10 percent, indicating that in remote regions the assumption of a 20 percent Ca content may be an overestimate. Using a soil-Ca content presented in Lee et al. (1999) as an input for the model of Tegen and Fung (1994) yielded much lower Ca deposition rates from soil dust than the above described approximation.

In order to obtain a better spatial distribution of deposition of base cations, the approach for soil dust with actual soil Ca content should be complemented with base-cation deposition modelled from inventories of emissions of base cations from industrial and combustion sources.

The uncertainty in atmospheric models can be demonstrated by the important disagreement between the different models, as was discussed by Holland et al. (1997). Differences in atmospheric sources of N gas emissions, transport, and resolution and representation of chemical reactions contributed to distinct spatial and temporal patterns of N deposition simulated by different models. Sofiev (1999) performed a model intercomparison to assess the uncertainties in deposition fluxes by comparing model results with measured deposition fluxes of S and N.

Apart from the uncertainties in the emission and deposition fields, there may be errors resulting from the scale used and from differences between the resolution of the various spatial databases. The 0.5° x 0.5° resolution for vegetation data, for example, does not have sufficient detail to include certain ecosystems such as wetlands. An evident example of a scaling error is the overlaying of low resolution deposition fields (5° x 5°) with high-resolution critical load values for terrestrial ecosystems (0.5° x 0.5°), as in this study. In reality, considerable variability occurs within the 5° x 5° deposition fields. This variability on small spatial and temporal scales may strongly influence the exceedance of critical loads.

Deposition fluxes are obtained from the 5° x 5° grid calculations of the STOCHEM model. Significant improvements can be achieved by:

1. Performing calculations on a 1° x 1° grid using a source receptor matrix derived from other atmospheric models. Such an approach could be used for regions such as Europe. On the global scale the matrices will become too large to handle with current computer resources.
2. As an alternative, the global STOCHEM calculations can be refined to a 1° x 1° grid by accounting for the local contribution as a function of local/regional meteorology and land

cover/land use. Such a method is similar to approximations already used for calculations of small-scale N deposition in Europe (EDACS, EUTREND).

3. A third alternative approach can be used if only country-scale emissions are available. This consists of establishing source-receptor matrices for NOx and NHx that summarise the various chemical and transport processes of the two species in the atmosphere. Whether or not this matrix can be assumed to be linear needs to be investigated in relation to the scale of the calculations (time scale of one year, spatial scale of hundreds of km). This approach is contained in the IMAGE2 models for computation of sulphur deposition (Alcamo et al. 1995) and is also appropriate for scenario analysis.

3. Photo-oxidants

Although there is a considerable amount of research on photo-oxidants, an important number of issues still remain as uncertainties. For instance, emission estimates of ozone precursors (nitrogen oxides and volatile organic compounds), both from anthropogenic and biogenic sources, require improvement and validation by suitably designed experiments on all scales. detailed information on the trends in concentrations of photo-oxidant precursors is also needed. The trend analysis for most precursors is at best restricted to a decade of modern measurements. This time scale needs to be at least doubled to put anthropogenic emissions in context. The vertical profile of precursors in the boundary layer and the free troposphere is another area requiring improvement.

The characterisation of chemical species has shown that there are many more compounds (VOCs) involved in environmental damage than initially thought. Now the question is whether all the important compounds and sources have been identified. Moreover, evidence exists that chemistry of VOCs takes place within the plant canopy and it is now recognised that chemical processes must be quantified. However, the chemistry of secondary products formed by ozone and OH attack is still unknown and laboratory studies must be carried out to identify the final products. A number of algorithms have been developed using plant specific emission rates, which have allowed for the development of models and the provision of emission estimates at regional and global scales. These algorithms can predict short-term variation of some VOC emissions but substantial modifications may be needed to predict the seasonality of emissions. Estimates of global biogenic VOC emissions have increased almost three fold in the last thirty years as more species are considered and improved base emission factors become available. In spite of the existing uncertainties, global estimates of biogenic VOC emissions are definitely far greater than anthropogenic emissions. The tropics remain the area of the world with the greatest emission rates and the greatest uncertainties due to the large species diversity and the lack of supporting data. VOC emissions will change in response to global change but the magnitude of these changes cannot currently be quantified.

Research is needed in the quantification by experiment of the various processes known to affect global tropospheric ozone, in particular how and where ozone is made in the troposphere, and to determine trends for reactive molecules such as ozone and free radicals, particularly OH. Research is also needed to quantify the global influence of halogen radical chemistry, particularly in ozone destruction, and nitrate radical chemistry. Another uncertainty involves detecting the presence of heterogeneous chemistry and quantifying its influence on free radical chemistry and ozone destruction.

It would also be very valuable to determine the impact of large-scale pollution of the troposphere by ozone and by reactive nitrogen compounds on climate and regional air pollution, and on fertilisation of the oceans and land surfaces. The impact of increased emissions of pollution from developing regions in Asia, South America and Africa needs to be studied, and understanding of the transport processes which affect the ozone budget improved.

Research is also necessary to remove the major uncertainties in the magnitude of many natural processes, including emissions from vegetation, from lightning and from the ocean and the potential impact of climate change. The identification of the full range of compounds emitted into the atmosphere from both natural and anthropogenic processes also requires further research.

Global distributions of the most important stable trace gases on tropospheric chemistry and measurements of many free radicals also needs study.

Heterogeneous processes of all sorts are either ignored or oversimplified in current models. For instance, the formation of aerosols, their processing in clouds, the related cloud processes and any reactions that occur on the particles need much more work before their contribution to the practical problem can be properly evaluated.

The validation of current models through model intercomparisons and properly designed and executed field trials is also an urgent need. These will certainly reveal deficiencies in the models that will need correcting and will help resolve the current disagreements between field experiments and model calculations on the role of NOx versus VOC limitations in photo-oxidant formation. Chemical transport models need to be validated on regional and sub-regional scales. More generally, the models currently in use are largely "episodic", capable of dealing with periods of only a few days; these must be adapted to give the long term results required for policy development. Much of the current work and increased computing power has concentrated - and continues to do so - on improving the details. However, policy makers require models capable of giving averages for a year or several years so that the likely effects of new policy measures for a foreseeable period can be evaluated. New methods will have to be developed to obtain such results from the present detailed models.

4. Heavy metals

There are also many uncertainties surrounding the assessment of the deposition and effects of heavy metals, especially in the Arctic. Major anthropogenic sources of atmospheric heavy metals within and outside the Arctic are fairly well recognised, however more must be done to update emission rates and volumes, and to generate better estimates of contaminant loads.

Within the Arctic, anthropogenic emission sources and fluxes of Hg and other heavy metals to the air need to be more accurately listed. Emissions should be measured as volumes of exhaust gases and heavy metal concentrations within exhaust gases from these sources. More information is needed on emission estimates from local authorities in non-Arctic nations. At this time, anthropogenic sources and fluxes are better understood than natural sources and fluxes, particularly for Hg. More emphasis needs to be placed on measuring emission rates of

heavy metals from natural sources such as volcanic eruptions and venting, sea-salt emissions (mostly Se), and re-emissions from aquatic and terrestrial surfaces.

A significant contributor to the total budget of heavy metals in the Arctic region is long-range air transport. An accurate estimate of heavy metal emissions from outside sources is essential for assessing the relative contribution of long range transport to total loadings. To help meet this need, the IGBP Global Emission Inventories Activity (GEIA) program is carrying out work to determine the spatial distribution of heavy metals emissions and generate maps using data on non-Arctic anthropogenic sources from 1995 for Hg. Hg emission inventories will be prepared for elemental Hg and bivalent Hg in gaseous phase and elemental Hg on particles. Emission maps for other heavy metals, particularly Pb and Cd, will also be updated for 1995. This work was expected to be completed by the end of 1999.

Two of the largest producers of Hg emissions to air, however, include China and Russia where data are limited. To estimate outside contributions of heavy metals to the Arctic environment, AMAP should support emission inventories in these two countries. Another issue discussed was the importance of the changing world conditions that could serve as principal drivers of change in air emissions, altering emissions substantially over time.

Both “dispersion” and “receptor” models have been developed as a way of estimating the extent to which emissions from distant sources contribute to contamination in the Arctic environment. To date dispersion models have principally been used by Canada, Norway, Sweden, Russia (via the UN ECE European Monitoring and Evaluation Programme-EMEP) and the United States.

AMAP countries should co-operate more closely to develop better dispersion modelling tools for assessing the contribution of heavy metals from outside sources. To do this better data are needed to meet the needs of modellers. Data improvements are also needed to generate more accurate emission data and maps, to ensure that meteorological data are available to the modellers and to allow verification of model results through measures of concentration of metals in air and precipitation and in the use of meteorological parameters.

Receptor modelling may prove useful for determining source apportionment in Arctic air. However, it was felt that a large number of metals would have to be measured to obtain reliable results for model verification. To verify models estimating pollutant transport from emission sources from within and outside the Arctic, data from a range of key locations is needed.

Available information on sub-lethal biological effects in Arctic organisms is limited for a number of reasons. Sub-lethal biological effects are difficult to detect in wild populations, as is collecting data on their effects. Additionally, Arctic species are not typically included in contaminant effects work. The most readily available information on the effects of heavy metals is at the level of individual tissues. Based on laboratory studies, observed levels of Cd and Hg in some Arctic marine birds and mammals are high enough to be of concern. However, observable effects in wild animal populations have been difficult to find. Exceptions are heavily contaminated sites, such as Minamata, Japan, where acute mercury related effects were seen in human and wildlife populations due to high industrial discharges of mercury.

Difficulties in detecting effects are related to several issues. There is a significant lack of correspondence between laboratory dose-response studies, where responses are linked to known dosing, and field studies where body tissues are analysed to determine tissue concentrations. Without data relating dose to tissue concentrations, field scientists cannot calculate extrapolations of exposure from their data. Laboratory scientists could do much by analysing and reporting tissue concentrations under known dosing regimens. Without such information, the relevance of laboratory data for assessing the biological effects of heavy metals in Arctic wildlife will remain limited.

5. Particulate matter

There is clear evidence of association between the concentration of particulate matter and health at levels of exposure commonly observed in developed countries. However, there are numerous gaps that need to be addressed in the immediate future to better assess the health impacts, and, consequently, to calculate the costs of abating particulate matter. Among the main issues, which require further research, the following are pertinent to the assessment of health effects (WHO, 1999):

- ***Composition of PM (size, chemical composition, mass, number or surface area):*** Data on the typical chemical composition of PM from different locations are still limited. This is crucial information, e.g. for studies on source apportionment and to further study the pollution transported over long distances. The size distribution of particulates in various pollution situations also needs to be better established.

- ***Epidemiological studies:*** The health effects associated with particulates need further detailed investigation. Age-specific mortality and morbidity data which will allow for spatial adjustment of the frequency of the health events must be obtained. It is also important to determine the applicability of American long-term studies on European populations, as well as the relevance of the exposure-response associations estimated from the currently available studies for very low particle concentrations, e.g. resulting exclusively from the long-range transport of pollution.

- ***Monitoring of PM concentrations:*** Currently, there are no comparable PM_{10} data available for larger parts of Europe and regions of other parts of the world. PM_{10} measurement sites have to be established. Other indicators of particulate matter, such as $PM_{2.5}$, should also be included in monitoring programmes.

- ***Emissions:*** Reliable PM_{10} and $PM_{2.5}$ emission inventories should be established. Data on emissions of primary particulates could be included in the list of pollutants covered by CORINAIR. The CORINAIR emission guidebook should ensure that comparable methods are applied to establish emission inventories for particulate matter. Some emission factors, e.g. for agricultural activities, re-suspension, natural emissions, etc. are still quite uncertain and should be supported by further investigations. Emissions from other parts of the world are also needed.

- ***Dispersion models:*** European models for secondary PM have been used internationally. They could be improved by better spatial resolution to allow more precise estimation of population exposure. The models for primary PM are still in the initial stages of development. These models should be improved and validated with measurement data. The inclusion of particulates into integrated assessment modelling is necessary to identify cost-effective measures.

6. Critical loads for acidification

The uncertainty in deposition estimates and sensitivity on the global scale is high, with the effects of N deposition in tropical ecosystems particularly poorly known. Rates of immobilisation and denitrification (in particular in tropical ecosystems) are also uncertain. In addition, acidification of soils is not only influenced by external inputs of acidity. In the long term, ecosystem acidification also results from the cation and anion balance during growth of vegetation, affecting proton release (Markewitz et al. 1998).

For the identification of acidification and eutrophication risks for terrestrial ecosystems, the most important causes of uncertainty seem to be the assumed sensitivity of tropical ecosystems to deposition of N and S. The deposition of base cations is also currently very uncertain outside the well-studied areas of Europe, North America, and to a lesser degree East Asia. As the sensitivity of some tropical ecosystems to N and S deposition is very high, small deposition flows of N and S can lead to exceedances. For these regions, therefore, the assessment is also very sensitive to uncertainties in deposition.

One way to improve these estimates is by stimulating manipulation of S and N inputs with realistic treatments in long-term ecosystem studies in unaffected and affected areas. Results from such experiments are essential for verifying dynamic ecosystem models that integrate the major vegetation and soil processes. However, it is unlikely that experimental data will be available within the next decade. For the meantime, therefore, an alternative would be to consult experts worldwide to assess the available research data so as to arrive at a system of default values. Regional studies, based on more detailed maps which better present the mosaic of ecosystems that could not be included with the 0.5^{o} resolution database used in this type of study, are also required.

Soil buffering capacity is based on properties of representative soil profile data; as the soils data is limited in some regions, global mean data were used. Field research with different realistic doses of acidity added to different soil types and vegetation types should be developed, including direct effects of atmospheric pollution on plants.

Growth of plants affects proton release through vegetation cation and anion exchange and leaching. This process, which may account for a considerable portion of acidification, has not been taken into account. There is a need for the development of models describing acidity release in ecosystems through plant growth and decomposition.

7. Critical loads for eutrophication

Bobbink et al. (1996; 1998) identified a number of major gaps in knowledge on effects of enhanced N inputs through deposition, including:

(i) quantified effects of enhanced N deposition on fauna are extremely scarce;
(ii) critical loads for N deposition to Arctic and alpine ecosystems are highly speculative; those for steppe grasslands, Mediterranean vegetation types, high altitude forests, and ecosystems on neutral and calcareous soils require further research;
(iii) most research carried out so far has focused on effects of enhanced deposition on trees only, and more research is needed to quantify effects on ground vegetation and (ground) fauna.

For temperate ecosystems outside Western Europe, there are major uncertainties in the permafrost regions and cold northern taiga and tundra ecosystems. On the basis of Bobbink et al. (1996), low critical load values were assumed for these systems. Critical N loads for the tropical ecosystems are entirely based on assumptions. Of most uncertainty are the susceptibilities of dry tropical ecosystems, including savannahs, dry tropical forests, semi-arid systems and tropical grasslands.

A further uncertainty is the influence of climate change and anthropogenic N inputs on the sensitivity of different ecosystems. This may be most important in temperate and cold climates, such as the above-mentioned Arctic, alpine, steppe and high altitude ecosystems.

Regional studies could be considered for those areas identified as potential risk areas, such as parts of South America, Western and Southern Africa and parts of Siberia. It should be noted that potential responses also need to be identified at a regional level.

Finally, this study indicates that acidification and eutrophication risks are more widespread than the well-known areas of Western and Eastern Europe, Eastern USA and Southeast Asia. These risks could even increase, following expected increases in emissions from agriculture (growing volume and use of fertilisers), transport and fossil fuel combustion. Including assessments of these risks within the context of (global) integrated assessment could provide useful information for environmental management, certainly when considering the combined impacts of acidification, eutrophication and climate change.

8. Effects of pollutants on health, materials, crops, etc.

The effects of NO_3 and SO_4 aerosols on human health are generally well documented in the literature. There is less data on linkages of ozone with chronic effects on mortality and morbidity than on the effects of aerosols. There is also a need to study the effects of SO_2 on chronic morbidity. With respect to the effects of VOCs on human health, there is a lack of data on the differences depending upon VOC specification. There is also a need for more work on the effects of NO_2 on humans at ambient levels.

Relying on available epidemiological evidence for estimating health effects associated with human exposure to ambient sulphate aerosols makes a quantitative assessment feasible with limited research resources and it uses a great deal of health effects evidence that is readily available. There are, however, several important uncertainties and limitations resulting from the limitations of the available epidemiological evidence.

The uncertainty surrounding the specific biological mechanisms that underlie the observed relationships in epidemiological studies, raise doubts about the confidence with which the results should be interpreted as causative. Epidemiology studies are able to demonstrate whether a statistically significant relationship exists between health effects and pollution concentrations, but the studies do not prove that the relationship is causal. Although there is laboratory and clinical evidence of health effects associated with sulphates, the exact biological mechanisms that underlie the observed epidemiological association have not been established.

There is also uncertainty about the relative harmfulness of sulphates versus other types of pollutant aerosols that are typically present in the ambient air. Sulphates are a significant proportion of the mix of fine particulate matter in the ambient air. Some epidemiology studies have included sulphate concentrations as a measure of pollution, as well as more comprehensive measures of particulate matter such as $PM_{2.5}$ or PM_{10}. While some, epidemiology studies have found a statistically stronger association between health effects and sulphates (e.g. Plagiannakos and Parker, 1988), others have found a stronger association with the more comprehensive measures of particulate matter (e.g. Dockery et al. 1992). Because of the typically high correlation among sulphates and other measures of fine particulate matter in the ambient air, it is difficult to statistically isolate the effects of sulphates alone in epidemiology studies.

The extent to which health effects occur at lower ambient sulphate concentrations are also subject to uncertainty. For sulphate aerosols, it remains uncertain whether there is a threshold concentration below which health effects no longer occur, or whether the slope of the concentration-response function diminishes significantly at lower concentrations.

The effects of SO_2 on materials are generally well documented, but a lack of understanding on the effects of other pollutants on, for example buildings or cultural assets. However, these effects may not be so important when considering acidity. No exposure-response data is yet available on the effects of ozone on paint and rubber etc. More research in this field would be welcome.

When considering the effects on crops, there is data on the direct and indirect effects of SO_2 and O_3 on crop yield and livestock, as well as on Nitrogen deposition as a fertiliser. However, there is a lack of knowledge on the interactions between pollutants and with pests, pathogens, climate, etc.

There are also many uncertainties in available estimates and interpretations of monetary valuation for changes in human health effects. Although it is quite clear that changes in human health have both financial and non-financial significance to human welfare, determining appropriate monetary measures of the total effect on human welfare is a difficult task. The uncertainty in the monetary estimates is probably greatest for premature mortality risks.

The first area of uncertainty in the monetary estimates for premature mortality is that there is little empirical economic evidence about how health status or life expectancy affects an individual's willingness to pay for changes in risks of premature death. Available willingness-

to-pay estimates for changes in risks of death are drawn primarily from samples of adults of average age distributions and average health status. It is possible that many of those at greatest risk of premature mortality because of air pollution exposure are elderly or in relatively poor health.

The second area of uncertainty in the monetary estimates for premature mortality is that most of the available estimates are for changes in the risks of accidental death rather than death due to illness, which is more the issue for pollution exposure. This is because the economic literature concerning monetary values for changes in risks of death has been able to use available data on wage differentials as a function of different levels of on-the-job risks of fatalities. It is uncertain whether individuals might have different reactions to risks due to illness rather than accidents, and how this might affect willingness to pay to avoid or reduce such risks. There is some evidence that risks of death due to particularly feared illnesses, such as cancer, are considered more abhorrent than risks due to accidents, but that evidence is limited.

9. Abatement methods and costs

When assessing abatement methods and costs under global environmental integrated assessment perspectives, some uncertainties are more likely to be found. This would be mainly because of the lack of data in many parts of the world, especially in the developing world. However, when considering this, and taking a look at widely recognised integrated assessment projects, such as the work done by IIASA with RAINS in ASIA, one can see that this is not a particularly difficult area regarding uncertainties. In this respect many assumptions and extrapolations can be made between the different parts of the globe without too much uncertainty.

The main strength of the RAINS model is the spatial optimisation of emissions to achieve given environmental quality objectives. There are good grounds for believing that RAINS systematically overestimates the costs of abatement because of the inclusion in the database of only end-of-pipe solutions. Other solutions (fuel switching, etc.) may be much more cost-effective at the national level (though this may impact on some parts of industry differently). A recent review (SEI, 1999) has found that there is a strong tendency for ex-ante estimates of costs to be far higher than the real costs. Representatives of industry tend to take a different view, based on the applicability and effectiveness of some of the measures included in RAINS.

It has also proved extremely difficult to extrapolate national data on a plant by plant level, leading to problems in the past when changing the scale of integrated assessment models (e.g. from continental to national). Problems can also arise because when modelling one tends to deal with idealised situations, as opposed to the actual situation in the industry.

10. Change of scales and data compilation

The lack of relevant data is a common experience. Within the environmental field, there are still serious data gaps. The quality of existing data is of equal concern. Causes of data gaps and poor data quality are complex and diverse.

There are inherent challenges in working with datasets on a global scale. From the perspective of GEO as a high-level global assessment, linkages of data across scale are particularly important. Given that, in general, only data with the same definition, standards and date of measurement can be safely aggregated to a regional or global level, even small discrepancies or gaps can make datasets incomplete or otherwise deficient. On the other hand, even with good quality data, aggregation and averaging may mask important spatial or temporal diversity. In large-scale aggregations, issues unique to smaller regions disappear. Therefore, the scale of aggregation and reporting of averages should be carefully matched with the scale of environmental issues or policies and the purpose of assessment.

10.1 Institutional constraints affecting data issues

The monitoring and data collection infrastructure of most developing countries is severely handicapped or non-existent due to limitations in resources, personnel and equipment. Constraints are also faced by international organisations - keeping well-trained personnel in publicly-funded institutions is difficult. In some cases, there is no organisation mandated to collect and report time-series data internationally on specific issues on a regular basis.

Data are reported for different geographical areas by different agencies and organisations. As a result, it may be impossible to use and compare otherwise valuable aggregated datasets in global and regional assessments.

The data management infrastructure of many countries is weak and data reporting is fragmented. Without a central coordination and collection system, environmental data may remain scattered across many sectoral organisations and departments. Another practical problem is that the databases must be constantly updated, otherwise they can include data that is no longer relevant to the issues. As a consequence, variables and indicators on impacts are poorly represented.

10.2 Technical constraints affecting data issues

In some cases the definition of what is being measured is vague and open to mis-interpretation, and in others national reporting is simply incompatible with international standards. There can be tremendous incompatibility between global and national datasets (for example, due to generalisations made when considering global issues or the use of different definitions or scales). Inconsistencies or even mistakes among international datasets (such as inconsistencies in definitions), etc can also be a problem.

Collection of time-series data requires permanent monitoring networks with adequate geographic coverage and sufficient resources. Although the availability of remotely-sensed data has led to improvements in the cost, quality and availability of environmental data, remote sensing cannot entirely substitute for measurements on the ground.

Time-series data rarely match between countries or across a whole region. Essentially, the problem is that 1990 data, for instance, from one country cannot be compared with similar data from another country for 1995. Similarly, if data for different indicators exist for different time periods, their comparison is problematic.

Various statistical methods are used to fill data gaps and smooth curves, or they are often filled with estimates provided by experts. While in the absence of real data these methods are necessary, the risks of using them should be understood. Furthermore, they are clearly not substitutes for monitoring, measurement and the verification of data obtained through remote sensing and on the ground.

Some variables are inherently difficult and/or costly to measure for large geographic areas; examples are the measurement of particulate matter in air and the measurement of biological diversity. Measuring the effectiveness of policy implementation may be equally challenging given that outcomes are often the result of several parallel policy actions. This makes the separation of the impact of one single policy from the others difficult.

Frequently, there are fundamental differences in data collection methods for data with the same label from different sources. Without going into a detailed analysis of data collection and measurement methods and standards, there is a risk that incompatible data may end up in aggregated datasets.

Comparing global datasets with regional and national datasets is a problem in itself since they will have been produced for different purposes, using different data processing techniques which may be valid for one scale but not for the other. Furthermore, for many variables and countries relevant data sources could not be found or accessed, and, if available, data often corresponded to different years among the sources.

Data may be inaccessible because of copyright issues, high cost, professional jealousy or organisational competition. Although some parameters are accurately and routinely measured, the information may be classified or otherwise publicly unavailable. Difficulty of access to data on shared aquifers and surface water is an example that occurs in many parts of the world.

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