Regional Air Pollution and Climate Change in Europe: An Integrated Analysis (AIR-CLIM)

Progress Report 2

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SUMMARY

Objectives

Despite the many overlaps of regional air pollution and climate change European policymakers have handled these two environmental problems separately up to now. One reason for this separate approach has been that policymakers do not have the quantitative information needed to develop policies that address both regional air pollution and climate change in Europe. This project aims to perform an integrated analysis of the linkage between the two problems in Europe and to produce results that are relevant to European policy. Specific objectives are:

1. To examine whether climate change will alter the effectiveness of agreed-upon or future policies to reduce regional air pollution-causing emissions in Europe, and vice versa.
2. To identify the relative importance and overlap of regional air pollution and climate change impacts under a consistent set of assumptions about future developments of emissions.
3. To identify and evaluate comprehensive policy strategies for controlling both regional air pollution and climate change in Europe.

Objectives for this reporting period were:

1. To identify the relative importance of regional air pollution and climate change impacts.
2. To identify joint targets and strategies to control regional air pollution and climate change.
3. To organize a mid-term review meeting and prepare a report on its results.

Compiling a Framework for Integrated Analysis

An integrated modeling framework is used to meet the objectives of the project. This framework consists of parts of two state-of-the-art integrated models covering regional air pollution in Europe (RAINS) and global climate change (IMAGE), supplemented by new components. RAINS is an integrated model of regional air pollution in Europe, describing the coupling between energy scenarios: country-scale emissions of sulfur and nitrogen; ambient concentrations and depositions of acidifying substances; and critical loads to ecosystems. The IMAGE 2 model is RAINS' counterpart for global climate change, coupling regional developments of energy and agriculture: emissions of greenhouse gases, and SO_2; changes in land cover and carbon fluxes between the biosphere and atmosphere; the build-up of greenhouse gases in the atmosphere; and flux of heat in the atmosphere and ocean. The additional components used in this project are:

(i) a module to calculate the ammonia (NH_3) emissions in Europe after 2010,
(ii) an atmospheric transfer matrix that links regional air pollution and climate change in the atmosphere,
(iii) maps of critical thresholds of regional air pollution in Europe that take into account climate change,
(iv) maps of critical thresholds of climate change in Europe.

Air pollution under climate change. Climate change may alter the dispersion, chemical conversion and removal of pollutants in the atmosphere. This, in turn, changes the pollutant concentrations in the atmosphere and the amount of sulfur and nitrogen species deposited. By deriving climate-changed source-receptor-matrices from a long-range transport model using changed weather patterns calculated by climate models it will be analyzed how the

distribution and conversion of air pollutants in Europe will be affected by climate change. Since these new source-receptor matrices will not be available until a late phase in the project, a provisional approach has been used to derive preliminary matrices. This is called the climate analogy approach. Thereby, that year among the observed (1986-1995) precipitation *patterns* was identified which is closest to the precipitation pattern under climate change for a selected future year. The existing source-receptor matrix of that 'analogous' observation year is used as a surrogate to simulate long-range transport of air pollutants under climate change.

Climate dependent critical acid deposition (critical loads). Critical loads depend among others on climate factors, which means that critical loads could be sensitive to climate change. Critical loads of acidity for forest soils are calculated with the so-called simple mass balance (SMB) model. The SMB model is the most commonly used method for deriving acidity critical loads in the UN/ECE context. Because weathering rates are influenced by soil temperatures and leaching by precipitation and evapotranspiration rates, the critical load of acidity is affected by temperature, precipitation and evapotranspiration rates. Thereby, in total an increase in temperature can (partially) be compensated by a decrease in precipitation surplus, i.e. precipitation minus evapotranspiration. Whether the precipitation surplus will increase or decrease under a changing climate depends on a fine balance between increasing precipitation and increasing evapotranspiration due to a higher temperature. Variation of both factors within reasonable ranges i.e. ranges expected in a warming climate up to 2100, indicated that critical loads will change at most about 10%.

Climate-dependent critical thresholds for SO_2 and NO_x (critical levels). For the integrated analysis of regional air pollution and climate change it is necessary to identify an effective way to simulate the potential impact of varying climate conditions on the direct effects of air pollutants on vegetation. For that purpose a model is developed that can be used to organize the available quantitative information on the response of different species to air pollutants.

The model is based on the assumption that the concentrations of pollutants in plants under present conditions when the ambient pollutant concentrations do not exceed the critical levels are 'safe' in-plant concentrations. The pollutant flux into the plant leaves under current climatic conditions - called reference flux - is estimated. In the second step the model calculates the fluxes under different climatic scenarios. With this information ambient concentrations can be derived for which the identified 'safe' in-plant concentrations are not exceeded. These ambient concentrations are used as climate-specific critical levels of air pollutants.

Critical climate thresholds. The critical climate approach is developed to assess negative impacts of climate change. Thereby, critical climate is defined as *a quantitative value of climate change, below which only acceptable long-term effects on ecosystem structure and functioning occur according to current knowledge*. The critical climate approach within AIR-CLIM is an equilibrium approach that assesses long-term effects of climate change on the production (NPP) of natural ecosystems. NPP losses in the range of 10 to 20% have been identified as acceptable based on an analysis of historic NPP variations. Climate Isoline Diagrams (CID) depict the allowable changes in temperature and precipitation for the predefined acceptable NPP losses.

Analysis of September Scenarios

An objective of the AIR-CLIM project is to derive reduction scenarios which consider reductions of both greenhouse gases and air pollutants. In this report the so-called *September scenarios* are analyzed that are a sub-set of the final AIR-CLIM scenarios. Start scenarios for the September (and the final) scenarios are the A1 and B1 scenarios of the SRES scenarios prepared for the Third Assessment of the IPCC as realized in the TIMER/IMAGE model. A1 and B1 do not assume any climate policy but rather stringent SO_2 policies. In a first step, these stringent SO_2 policies are replaced by 'AIR-CLIM' policies that keep the level of SO_2 reduction on the level of 2010. These AIR-CLIM reference scenarios are called A1-SR and B1-SR (SR for Sulfur Reference).

The September mitigation scenarios are so-called stabilization scenarios i.e. scenarios in which the CO_2 concentration is stabilized at a certain level. For A1 mitigation measures are assumed for which the CO_2 concentration stabilizes at 550 ppm; for B1 the respective level is 450 ppm. The SO_2 policies for these scenarios are as stringent as for the original A1 and B1 scenarios. The resulting mitigation scenarios are called A1-550-SA and B1-450-SA (SA for Sulfur Advanced Policy).

The analysis carried out so far within AIR-CLIM is preliminary as the methodology has still to be refined at some points. Some components (as the climate-change SRMs and the cost module) are to be added and the emission scenarios to be finalized. However, some preliminary scientific conclusions can be derived from the analysis of the September scenarios:

Emission trends. CO_2 emissions are expected to peak around 2040 to 2060 and then to decline. The emissions of SO_2 and NO_x in Europe are expected to decline to the levels set in the LRTAP Protocols in the next years and afterwards to stabilize or slowly to decline further. The global SO_2 emissions will peak around 2030 to 2040 and then decline. Assuming that countries without international agreements on SO_2 emission reductions will react similarly as Europe and Northern Europe to high SO_2 levels the decline will be steep and the global SO_2 emissions in 2100 about the same level as in 1990 or lower.

Costs of SO_2 emission reduction. For OECD Europe, the costs to achieve 80% reduction of the 2050 SO_2 emissions would take around 0.1% of the 2050 Gross Regional Product (GRP) for the A1-SR scenario, i.e. the scenario with the highest SO_2 emissions under analysis here. The costs for Eastern Europe to achieve a similar reduction share would account for 0.4% and for the Former USSR for 0.5% of GRP.

Impact of SO_2 on climate change. Contrary to earlier studies, only a small effect of SO_2 emissions on climate change *in 2100* is calculated. The reason for this is the decrease of the (global) SO_2 emissions to 1990 levels or lower while former studies assumed a continuing increase. Higher SO_2 emissions delay (but do not avoid) the exceedance of critical climate values in Europe.

Impact of climate change on regional air pollution. As climate-change SRMs are not yet available, the climate analogy approach has been used to calculate regional air pollution under climate change. Using this approach the impact is small. However, the analogy approach is very crude as e.g. changes in wind pattern are not taken into account. It is expected that SRMs derived from results of the EMEP model calculated with GCM output will be better. Only with these new SRMs the question can be answered how much regional air pollution is affected by climate change.

Impact of climate change on critical deposition (loads) and its exceedances. Under climate change the critical loads increase, i.e. the ecosystems become less sensitive with time, with the exception of Southern Europe. However, even under the lowest deposition scenario, the critical loads are still exceeded in some areas (Germany, UK, East Europe) in 2100.

Impact of climate change on critical concentration (levels). Critical levels increase in Central and Southern Europe under climate change. The reason for this is that in these areas the temperatures increase *and* precipitation decreases. Therefore, the stomata of the plants are more often closed and the uptake of pollutants by plants is reduced, the ecosystems become less sensitive. Critical levels decrease in some parts of Northern Europe. In that area temperature also increases but there is sufficient precipitation so that the stomata are not less often closed as nowadays. The increase of critical levels is much more marked for the A1-SR scenario than for the B1-SR and the B1-450-SA scenarios.

Critical climate and its exceedances. For current precipitation levels only severe temperature increases will lead to an exceedance of the acceptable effect of 10% net primary production (NPP) loss. Only in some areas in Southern Europe lower critical temperature changes are found. If current precipitation levels are reduced by 40%, in some areas temperature has even to *decrease* to avoid net primary production losses of more than 10%.

Three different types of responses can be distinguished: (1) Large parts of Northern Europe are only slightly sensitive to decreased precipitation levels, even if the temperature increases. (2) Middle Europe becomes less sensitive to reduced precipitation if the temperature increases. This is because higher temperatures stimulate NPP. (3) Southern Europe becomes even more sensitive to precipitation reductions for higher temperature.

Up to 2050 critical climate values will be exceeded only in a few areas in Southern and South-eastern Europe. The exceedance area increases up to a maximum of 14% of European area until 2100. Decreasing precipitation rates in combination with increasing temperature is responsible for this. The A1-SR scenario results in the largest area in which the critical climate is exceeded. The smallest area is computed for the B1-450-SA scenario.

Development of areas for which the various critical thresholds are exceeded. While the area for which critical climate is exceeded will increase with time, the exceedance area for acid deposition will decrease. Thereby even in 2100 the exceedance areas for critical loads are still larger than those for critical climate.

It can tentatively be stated that climate change will make European vegetation in most regions less sensitive to acid deposition. Taking into account the emission trends the impacts of regional air pollution will decrease while the impacts of climate change increase. Different problems will be important in different regions: regional air pollution in Central and Northern Europe, and climate change in Southern Europe.

1 INTRODUCTION

1.1 Background

Among the many challenges facing Europe as a community are the environmental problems that transcend its borders. One such challenge – regional air pollution – has been partially addressed during the last decade through negotiation of international agreements under the 1979 Convention on Long-Range Transboundary Air Pollution (LRTAP). These agreements have led to partial controls of some of the pollutants that cause regional air pollution.[1]

Policies to control another problem – climate change – have been negotiated at the so-called Conferences of the Parties (COP) in Berlin (1995), Geneva (1996), Kyoto (1997) and Buenos Aires (1998) under the 1991 U.N. Framework Convention on Climate Change (UNFCCC). At the COP in Kyoto a protocol was agreed on that is yet not come into force as so far (March 1999) only two states have ratified it. According to the Kyoto Protocol the EU has to reduce their greenhouse gas emissions by 8% until the first commitment period (2008–2012) compared to 1990.

There are important overlaps between regional air pollution and climate change from the perspective of both policy and science:

1. *Climate change may alter the environmental impacts of regional air pollution, and vice versa*:
   Up to now, one of the main objectives of policies to control regional air pollution (as compared to urban air pollution policy) has been to protect Europe's soils and vegetation. For example, an international treaty to reduce ozone concentrations, acid and nitrogen deposition in Europe (the 'Gothenburg Protocol' signed on 1 December 1999) based its reduction targets on the degree of protection of ecosystems in Europe. However, climate change could alter the effects of the treaty because:

   (1) Climate change is likely to alter European weather patterns, and this will affect the distribution of air pollutants throughout Europe;
   (2) Climate change will lead to long-term changes in temperature and precipitation that will affect the rate of acidification of soil and water.

   Hence, policies that are aimed to reduce regional air pollution impacts in the soil and water under current climate conditions, may not be successful under future climate conditions (and some might be more successful). Conversely, the level of regional air pollution also will have an effect on climate change and its impacts. For example, the emissions of sulfur dioxide (an important regional air pollutant) result in a layer of sulfate particles (aerosol) in the European atmosphere, and these particles reflect solar radiation and partly mask climate warming in Europe.

[1] Here, the term 'regional air pollution' is used to mean transboundary air pollution problems that occur in Europe that result in (1) high ground-level concentrations of ozone, sulfur dioxide, nitrogen oxides and other substances, (2) the deposition of trace toxic substances, and (3) acid deposition due to sulfur and nitrogen in the atmosphere.

2. *The causes of climate change and regional air pollution are linked in the European economy*:
   The issues of regional air pollution and climate change are linked in various ways in Europe's economy. For example, changes in the amount and types of fuels that are consumed will affect the rate of emissions of both regional air pollution-causing substances and greenhouse gases. At the same time deliberate policies to reduce regional air pollution-causing emissions, such as switching from high-sulfur coal to low-sulfur natural gas, will also reduce the emissions of some greenhouse gases.

3. *Not only the causes, but also the impacts, of regional air pollution and climate change are linked in the economy*:
   For instance, changes in temperature and precipitation will affect the rate at which regional air pollution corrodes building materials. Another example is that both regional air pollution and climate change are important sources of environmental stress to forests, and this stress could eventually endanger the ecological and economic viability of these forests.

Despite these overlaps European policymakers have handled these two environmental problems separately up to now. One reason for this separate approach has been that policymakers do not have the quantitative information needed to develop policies that address both regional air pollution and climate change in Europe. This project aims to perform an integrated analysis of the linkage between the two problems in Europe and produce results that are relevant to European policy.

1.2 Previous Studies

Some research has already been carried out to link regional air pollution and climate change issues. With regard to impacts on freshwater streams, a study of catchment processes in Finland found that on the one hand the direct impacts of climate change almost cancel out (Forsius *et al.*, 1997), i.e. the increase in precipitation is compensated by higher evapotranspiration due to the temperature increase, resulting in only a small change in runoff. On the other hand the influence on nitrogen processes (leaching) can be considerable. It is, however, an open question how this translates to other climatic regions in Europe. With regard to vegetation impacts, (Johnson *et al.*, 1995) found that elevated CO_2 and nitrogen deposition had significant effects on available phosphorus in the soils of a ponderosa pine forest in the western United States. These, and other local studies (such as those summarized in (Grennfeldt *et al.*, 1995)) are useful for the insight they give into the interaction of processes relevant to both regional air pollution and climate change, but they cannot be generalized to the European scale.

Current work at the International Institute for Applied Systems Analysis in Austria is concerned with linking climate change and sulfur dioxide impacts on European crops (Fischer, Amann, 1996). Several other research projects have dealt with climate change impacts and agriculture (e.g. (Harrison *et al.*, 1995), (Semenov *et al.*, 1996)). Results of these studies are useful to get insights in the sensitivities of particular crops to climate change and increased CO_2 levels. (Harrison *et al.*, 1995), for example, found that currently important crops in Europe will benefit from climate change (e.g. main yield improvement is 50%). But in our opinion it is still an open question whether the results can be generalized throughout the European continent, since most of the projects describe the impacts on the local scale. Moreover, the studies only analyse a limited number of combinations of temperature, precipitation, and CO_2, derived from General Circulation Models (GCM). An aim of the AIR-

CLIM project is to develop an approach suitable for the evaluation of various climate change options on the European scale agriculture.

In a study that came most close to the proposed study ((Alcamo *et al.*, 1995), (Posch *et al.*, 1996)) a first attempt was made to use consistent scenarios of sulfur emissions to assess their impacts on terrestrial ecosystems (critical loads for deposition and potential vegetation change for climatic warming). The studies showed that higher sulfur emissions increase the exceedance of critical loads, but reduce the effects of a climate warming due to increased amounts of sulfate aerosols in the atmosphere, thus demonstrating the importance of linking the climate system with regional air pollution. The framework outlined in those two studies will be greatly expanded and used for the assessments in this project.

1.3 Objectives

The overall goal of this project is to provide scientific information about key policy-relevant issues concerning the linkage between regional air pollution and climate change in Europe. Specific objectives are:

1. To examine whether climate change will alter the effectiveness of agreed-upon or future policies to reduce regional air pollution-causing emissions in Europe, and vice versa.
2. To identify the relative importance and overlap of regional air pollution and climate change impacts under a consistent set of assumptions about future developments of emissions.
3. To identify and evaluate comprehensive policy strategies for controlling both regional air pollution and climate change in Europe.

Objectives for this reporting period were:

1. To identify the relative importance of regional air pollution and climate change impacts.
2. To identify joint targets and strategies to control regional air pollution and climate change.
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2 Modeling Framework and Components

2.1 Integrated Modeling framework

Purpose of this Task

A tool is assembled for examining the linkage between two important environmental problems in Europe: climate change and regional air pollution.

Significance of this Task to Policy and Science

The framework will enable the analysis of two environmental problems - climate change and regional air pollution - together in an integrative way. That means the linkages of these two issues are taken into account on all levels. From the policy perspective, it will thus be possible to provide quantitative information to support European policymakers in developing policies that address both regional air pollution and climate change in Europe. From the scientific perspective the approach provides a method for harmonizing information from different disciplines into a single integrated framework.

Analysis to Date

An integrated modeling framework[2] (Figure 1) is used to meet the objectives of the project. This framework consists of parts of two state-of-the-art integrated models covering regional air pollution in Europe (RAINS) and global climate change (IMAGE), supplemented by new components. RAINS is an integrated model of regional air pollution in Europe, describing the coupling between energy scenarios: country-scale emissions of sulfur and nitrogen; ambient concentrations and depositions of acidifying substances; and critical loads to ecosystems (Alcamo *et al.*, 1990), (Amann *et al.*, 1995). The IMAGE 2 model is RAINS' counterpart for global climate change, coupling regional developments of energy and agriculture: emissions of greenhouse gases, and SO_2; changes in land cover and carbon fluxes between the biosphere and atmosphere; the build-up of greenhouse gases in the atmosphere; and flux of heat in the atmosphere and ocean (Alcamo *et al.*, 1998). The additional components used in this project are:

(i) a module to calculate the ammonia (NH_3) emissions in Europe after 2010,
(ii) an atmospheric transfer matrix that links regional air pollution and climate change in the atmosphere,
(iii) maps of critical thresholds of regional air pollution in Europe that take into account climate change,
(iv) maps of critical thresholds of climate change in Europe.

Indicators. For regional air pollution, the following indicators are used in the study: atmospheric concentrations of sulfur dioxide (SO_2), and nitrogen dioxides (NO_x), and deposition of sulfur and nitrogen. Together with ozone these are the regional pollutants that are currently receiving the most attention from European policymakers because there is a clear connection between these pollutants and the acidification of soil and surface waters, health impacts, material damage and other impacts (for a recent overview, see (Grennfeldt *et al.*, 1995)). Ozone is not included in the AIR-CLIM project because of the project's limited scope. Nonetheless, it is intended to extend the analysis to this pollutant in a follow-up project as well as to other potentially important regional air pollutants, e.g. persistent organic pollutants and heavy metals[3]. In order to compute the atmospheric concentrations of SO_2 and NO_x, and the deposition of sulfur and nitrogen, emissions of the following substances are taken into account in this study: nitrogen oxides, sulfur dioxide, and ammonia.

As indicators of climate change surface temperature and precipitation are selected. Different temporal scales of these data will be used, depending on the type of analysis. To compute climate change, it is necessary to take into account the global emissions of a wide range of greenhouse gases including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), as well as emissions that lead to the formation of ozone in the atmosphere.

[2] In this study the expression 'framework' is more appropriate than model because many of its components are not electronically 'hard' linked, i.e. they are not components of the same computer programs. In some cases output from one component has to be processed externally before used as input to the next component.

[3] Another reason not to analyze persistent organic pollutants and heavy metals in this study is that there is insufficient scientific information about these substances to conduct an integrated analysis. For example, an integrated analysis requires information about source-receptor relationships for different regional air pollutants. While this information exists for ozone, nitrogen and sulfur in Europe's atmosphere, it is only now being developed heavy metals. For persistent organic pollutants, whereas, there are no emission inventories available. This study, however, can provide a strong foundation for a follow-up integrated analysis of these other pollutants.

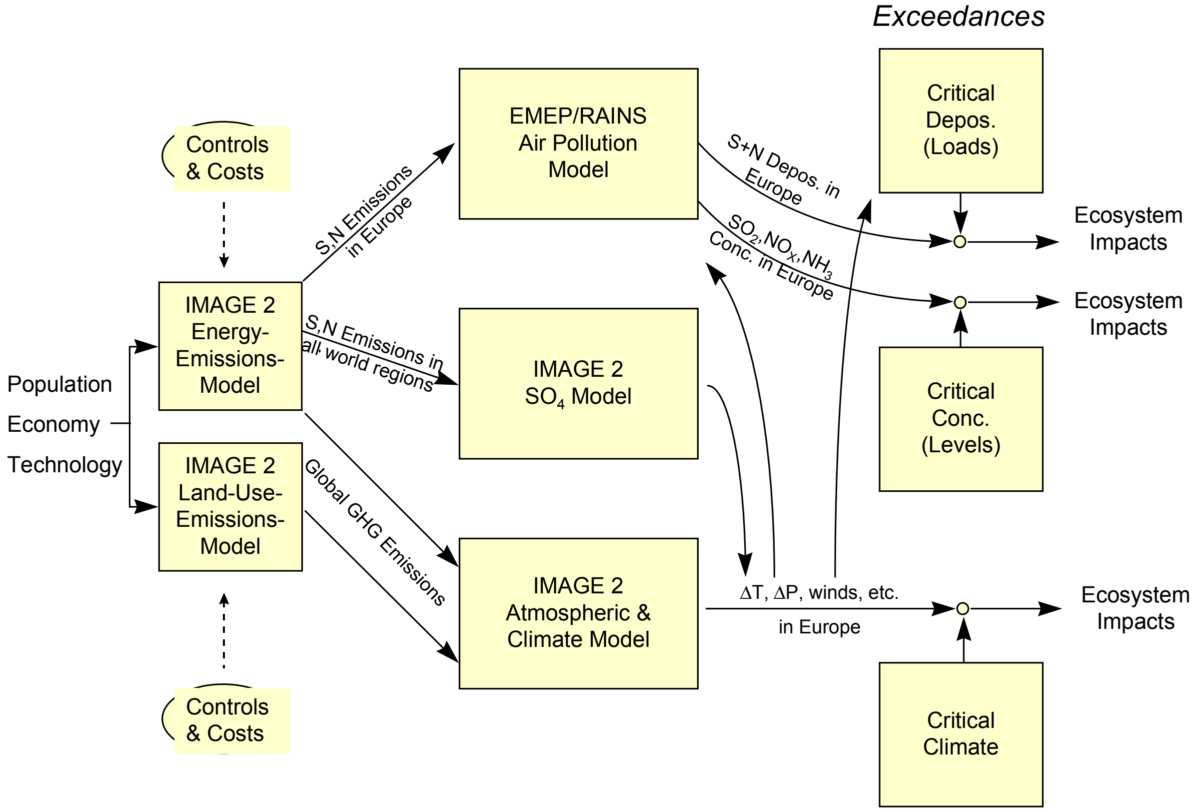

Figure 1 Integrated modeling framework for climate change and regional air pollution

Global emissions. Using the IMAGE 2 model, time series of greenhouse gas emissions, precursors of ozone (including NO_x), and SO_2 are computed for 13 world regions (regions include Western Europe, Eastern Europe, and the European part of the former USSR). This information is needed to compute climate change in Europe (see below). The emission calculations are based on scenarios for the consumption of energy, the level of industrial activity, and land use activity, for the years 1990-2100. The consumption of energy, in turn, is computed from the growth in population and economy and assumptions about technological development (De Vries *et al.*, 1994). Emission factors for the different gases take into account regional differences in types of energy equipment and other regional factors.

European country emissions. Country-scale emissions from the RAINS model are then used to downscale emissions important to regional air pollution from the regional- to the country-level. This information is needed to compute regional air pollution in Europe (see below).

Regional Air Pollution without Climate Change. To compute grid-scale atmospheric concentration and deposition of regional air pollutants from country-scale emissions, the source-receptor matrices (SRMs) contained in the RAINS models are used. These matrices summarize the various chemical and transport processes of sulfur, nitrogen, ozone, and other substances in the atmosphere, and link emissions to depositions by linear equations. The European country-to-grid matrices are derived from EMEP (European Monitoring and Evaluation Programme) model results and are based on average annual data for the period 1985 to 1994.

Regional Air Pollution under Climate Change. It is likely that climate change will lead to long term and seasonal changes in wind and precipitation patterns in Europe. These changes will, in turn, cause changes in the pattern of acid deposition (sulfur and nitrogen) in Europe. Thus, new SRMs are needed to reflect these changes (see Section 2.2).

Climate Change and Sulfate Aerosol. After SO_2 is emitted to the atmosphere, a fraction of it is re-deposited within hours or days as wet and dry sulfur deposition. The remaining air fraction will form SO_4^{2-} aerosols, which are important from the climate change perspective because they reflect a portion of the sun's incident radiation. The build-up of SO_4^{2-} aerosols in the troposphere is computed with a linear source-receptor matrix contained in the IMAGE 2 model (Alcamo *et al.*, 1998). The matrix is derived from the two-dimensional global model of atmospheric chemistry of TNO (Roemer, 1991), (Baart *et al.*, 1995). A portion of the tropospheric aerosol stems from natural sources such as biogenic emissions of dimethylsulfide and volcanic emissions of SO_2. This portion is assumed to remain constant at its current estimated level. The effect of SO_4^{2-} aerosol on increasing atmospheric albedo and cooling the atmosphere is estimated with the formulation of (Charlson *et al.*, 1991), together with updated coefficients. Other potential effects of SO_4^{2-} on the atmosphere, such as changes in cloud cover/depth and occurrence of precipitation, are not taken into account.

Climate Change and Temperature and Precipitation. Climate change is computed by the coupled atmosphere-ocean climate submodel of IMAGE 2 (De Haan *et al.*, 1994), taking into account SO_4^{2-} aerosols and the build-up of greenhouse gases. The main outputs of the climate submodel are changes in precipitation and surface temperature. Zonal averages from the climate submodel are scaled down to a global terrestrial grid of 0.5° latitude x 0.5° longitude, using results from the climate model of the Max Planck Institute for Meteorology (MPI) (Cubasch *et al.*, 1992) and an updated version of the climate data base of (Leemans, Cramer, 1991).

Although estimates of regional climate change from climate models are uncertain, they are considered adequate by the scientific community for conducting impact analysis of the type presented in this paper. Moreover, a sensitivity analysis presented in (Alcamo *et al.*, 1995) indicates that the general approach of our impact analysis is robust even when the uncertainty of regional climate calculations are taken into account.

Evaluation of impacts. Once calculations are made of regional air pollution and climate change, these data are used to evaluate the impacts of these problems. This framework uses two different approaches to evaluate impacts of regional air pollution and climate change.

(i) The 'risk of impacts', by comparing levels of regional air pollution and climate change against their 'critical thresholds' (see Sections 2.3 to 2.5).
(ii) The 'environmental balance sheet', by compiling and comparing the abatement costs for different scenarios (see Section 2.7), and a measure of impacts for different scenarios.

Scenarios. The framework is used to develop scenarios which explore the identified issues. The scenarios cover the time from 1995 to 2100, with a spatial resolution ranging from the country-scale to grid-scale, and consist of:

(i) Emissions leading to regional air pollution and climate change;
(ii) Changes in the atmosphere including the build-up of regional air pollutants and greenhouse gases together with deposition of air pollutants and changes in temperature and precipitation;
(iii) Impacts of climate change and regional air pollution based on critical thresholds and an environmental balance sheets; and finally,
(iv) Abatement costs for the reduction of air pollutants and/or greenhouse gases compared to a reference scenario.

Summary of New Developments Since First Progress Report and its Significance

The framework was refined and applied to a scenario set. The framework allows to analyze scenarios that address both regional air pollution and climate change in Europe.

2.2 Air Pollution and its Dependence on Climate Change

Purpose of this Task

Climate change may alter the dispersion, chemical conversion and removal of pollutants in the atmosphere. This, in turn, changes the pollutant concentrations in the atmosphere and the amount of sulfur and nitrogen species deposited, and thus influences the exceedance of critical levels and loads.

The purpose of this task is to analyze how the distribution and conversion of air pollutants in Europe will be affected by climate change. This will be done by deriving climate-changed source-receptor-matrices from a long-range transport model using changed weather patterns calculated by climate models (see Section 2.2.1). Since these new source-receptor matrices will not be available until a late phase in the project, a provisional approach has been used to derive preliminary matrices. This is called the climate analogy approach (see Section 2.2.2).

Significance of this Task to Policy and Science

From the policy standpoint this task is important because existing agreements to control sulfur dioxide emissions are based on reducing sulfur deposition under current climate conditions. However, if climate conditions change, then the goals of reducing sulfur deposition may not be met at all locations.

From the scientific perspective the analysis is one of the first to indicate how important climate change quantitatively is for atmospheric processes.

2.2.1 Climate-changed Source-Receptor-Matrices

Analysis to Date

Source-receptor matrices are used to calculate grid-scale atmospheric concentration and deposition of regional air pollutants from country-scale emissions. These matrices summarize the various chemical and transport processes of sulfur, nitrogen, and other substances in the atmosphere, and link emissions to depositions by linear equations. The present country-to-grid matrices for acidifying pollution are derived from model results of the EMEP Lagrangian Acid Deposition Model (LADM) and are based on actual meteorology for the period 1985 to 1994 (see (Barrett, Berge, 1996) for a description of the LADM model).

It is likely that climate change will lead to long term and seasonal changes in wind and precipitation patterns in Europe. These changes will, in turn, cause changes in the pattern of air pollution in Europe. Thus, new SRMs are needed to model air pollution under climate change. The idea is to feed climate data calculated by a climate model for a specific scenario into LADM.

Table 1 Climate data relevant in LADM (Barrett, Berge, 1996)

Climate Data	Factor affected
Horizontal wind speed	Trajectories
Ground precipitation	Wet deposition
Vertical velocity	Dry deposition
Surface pressure	Dry deposition
2 m temperature	Dry deposition
Turbulent stress	Dry deposition
Turbulent heat flux in the surface layer	Dry deposition
Relative humidity	Dry deposition
Mixing layer height (dependent on temperature gradient)	Chemical reactions Emission source intensity Deposition
Cloud cover	NO_2 dissociation
Temperature	Chemical reactions

Table 1 summarizes the main climate data that influence the calculations of LADM. LADM is a Lagrangian model in which the transport term of the (two-dimensional) mass balance equation is described according to defined trajectories. These trajectories are calculated from horizontal wind vectors. Physically, pollutants are removed from the atmosphere by dry and wet deposition. Wet deposition is due to precipitation, dry deposition is influenced by turbulence, etc. Chemically, pollutant species are removed by chemical conversion processes. These are influenced by temperature, cloud cover, and the height of the mixing layer. The horizontal wind vector and precipitation are probably the most important climate variables influencing the LADM results.

The grid used by LADM is the EMEP150 grid i.e. a grid with a 150 km grid length defined in polar stereographic projection (see Appendix A in (Posch *et al.*, 1999) for a definition). Although only annual or monthly pollution levels are calculated in the end, the air quality model needs 6 hourly input data to reasonably simulate the atmospheric processes.

Due to limited computer power for long climate simulations only very low resolutions can be used in global coupled atmosphere-ocean models (CGCMs) (at present 2.8° or 5.2° grid equivalent to grid lengths of about 300 or 500 km). With such resolutions the development of weather systems cannot be modeled appropriately because physiographic features like the land-sea distribution and smaller scales of the orography are lost (Cubasch *et al.*, 1999).

With the time-slice technique high resolution simulations can be run in a relatively inexpensive way. In the time-slice technique a long CGCM simulation is repeated for a certain period (e.g. 10 years) using a high resolution atmospheric model (AGCM) which takes initial and sea surface boundary conditions from the CGCM simulation (Machenhauer *et al.*, 1998).

In the EU project SIDDACLICH Cubasch *et al.* carried out (among others) a time-slice experiment with the AGCM ECHAM4 (Cubasch *et al.*, 1999). In this experiment the resolution was 1.1° (about 100 km at equator). The boundary data were taken from a

ECHAM4/OPYC run with a resolution of 2.8° for the IS95a scenario. 6 hourly data were calculated for two time periods: 1971-1980 and 2041-2050.

Before the SIDDACLICH project no time-slice experiments had been carried out for a transient simulation with such a high resolution and such long integration times. The results formed an integral part of the 2nd scientific assessment of the IPCC and in particular were an important strand in the scientific evidence behind the main conclusion of 'a discernible human influence' on climate (Cubasch *et al.*, 1999).

The results of these experiments are stored in a database at the Deutsche Klimarechenzentrum (DKRZ) in Hamburg which kindly provided the data for this project. At present the data are transferred to the format needed for LADM. After that LADM runs will be carried out and the results evaluated. In the first step, major systematic differences will be identified between the LADM results for present climate in 1970s as calculated by the GCM and the LADM calculations with actual meteorology. In the next step, the effect on acidifying pollution of changed climate will be analyzed based on the LADM computation for the future GCM climate in the 2040s. Based on these results an interpolation scheme will be developed.

Summary of Progress to Date and its Significance

An approach has been outlined and appropriate climate data identified and provided. The analysis will be one of the first to indicate the quantitative importance of climate change for atmospheric processes based on modeled climate data. It will help to answer the question whether the objectives of the air pollution policies decided on in the last decades will be impaired in a significant way by climate change.

Future Work

The GCM output will be prepared as input to LADM. LADM runs will be carried out and new SRMs derived which will then be evaluated. Based on the results of the evaluation an interpolation scheme will be developed and the new SRMs applied in the AIR-CLIM project.

2.2.2 Climate Analogy Approach

Analysis to Date

The goal of this approach is to find among the observed (1986-1995) precipitation *patterns* (not amounts!) the one which is closest to the precipitation pattern under climate change for a selected future year; and then use the source-receptor matrix of that 'analogous' observation year as a surrogate to simulate long-range transport of air pollutants under climate change.

In mathematical terms, let p_{ki} be the annual precipitation of observed year k in grid cell i=1,..,N, and q_{li} the simulated 'climate-changed' precipitation for (future) year l in the same grid cell. Then we minimize the following function:

$$F_{kl}(a) = \sum_{i=1}^{N} \left(a\, p_{ki} - q_{li}\right)^2 \qquad (1)$$

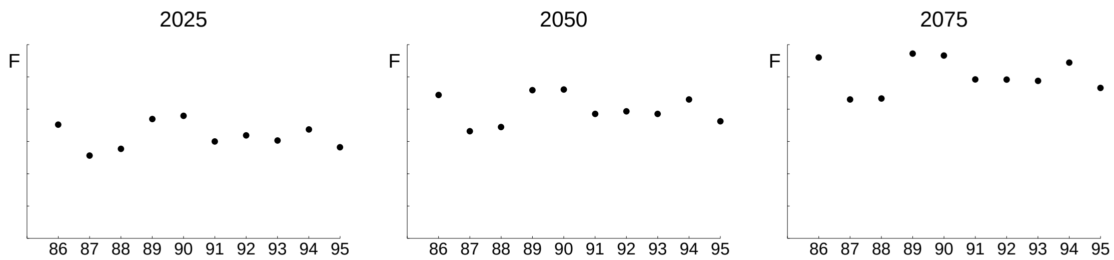

Figure 2 Value of the precipitation goal function F for three future reference years for each of the ten years of observations. In all three cases F attains its smallest value for the year 1987 and thus the SRMs of that year are chosen as surrogate climate-change SRMs.

The minimum is obtained by setting $F_{kl}/a=0$, yielding the optimal a for years k and l:

$$a_{kl} = \sum_{i=1}^{N} p_{ki} q_{li} / \sum_{i=1}^{N} p_{ki}^2 \qquad (2)$$

The smallest of the minima $F_{kl}(a_{kl})$ for the different year combinations (k,l) indicates which observed year k is best suited for (future) year l, and the surrogate precipitation field is given by $a_{kl}p_{ki}$.

Similarly, for temperatures t_{ki} (observed values) and s_{li} (future years), the function

$$G_{kl}(b) = \sum_{i=1}^{N} \left(t_{ki} + b - s_{li}\right)^2 \qquad (3)$$

could be minimized. However, since temperature has a smaller influence on critical load values, it was decided to optimize with respect to precipitation. As illustrated in Figure 2, the precipitation pattern of 1987 turns out to be the closest to the simulated ones for all reference years. Thus the 1987 source-receptor matrices (SRMs) are used as a surrogate for climate-change SRMs in the calculation presented in this report.

Summary of Progress to Date and its Significance

The climate analogy approach presented above has been newly developed during 1999. Therefore, this report is the first one to describe the potential influence of climate change on the dispersion of pollutants and its influence on critical load exceedances.

Future Work

As described above, in year 2000 we will compute new SRMs using the EMEP model and climate change data. These new SRMs will supersede the SRMs computed with the climate analogy approach and the climate analogy approach will not be further pursued.

2.3 Critical Loads and Their Dependence on Climate Change

Purpose of this Task

Critical loads depend among others on climate factors. This dependence provides an important linkage between air pollution and climate change. Therefore, the purpose of this task is to include the dependence of critical loads on climate change in the AIR-CLIM integrated modeling framework.

Significance of this Task to Policy and Science

Critical loads are used since more than five years to support emission reduction policies on a European scale. This is evidenced by the recently signed Protocol to Abate Acidification, Eutrophication and Ground-level Ozone ('Gothenburg Protocol' to the LRTAP Convention) and the preparations for the EU Emission Ceilings Directive. The analysis within the AIR-CLIM project aims at clarifying whether climate change will improve or counteract the effectiveness of these policies. From a scientific perspective it is of interest how the sensitivity of ecosystems to deposition of sulfur and nitrogen is influenced by climate change.

Analysis to Date

Methods for calculating critical loads have been developed in several UN/ECE workshops and are summarized in a Mapping Manual edited and maintained by the Task Force on Mapping under the UN/ECE Working Group on Effects (Gregor *et al.*, 1996). In the AIR-CLIM project we consider critical loads for forest soils, calculated with the so-called simple mass balance (SMB) model, the most widely used method for deriving critical loads under the LRTAP Convention (Posch *et al.*, 1999). In this model the soil is treated as a homogeneous compartment with depth equal to the rooting zone. Defining a critical (maximum) leaching of ANC (acid neutralization capacity), the excess leaching, Ex_{le} (eq/ha/yr), from the root zone for a given deposition of S and N is given by

$$Ex_{le} = S_{dep} + (1 - f_{de})\, N_{dep} - BC_{dep} - Cl_{dep} + BC_w - Bc_u + (1 - f_{de})\left(N_i + N_u\right) - ANC_{le(crit)}$$

where BC stands for the sum of base cations ($BC=Bc+Na=Ca+Mg+K+Na$), f_{de} ($0 \le f_{de} \le 1$) is the so-called denitrification fraction (a soil property) and the subscripts *dep*, *w*, *i*, *u* and *le* stand for deposition, weathering, immobilization, (net) growth uptake and leaching, resp. Combinations of N_{dep} and S_{dep} yielding $Ex_{le}=0$ are called **critical loads**. The above equation does not define unique critical loads for S and N, only a functional relationship between them, called the critical load function (see Figure 3). If depositions are such that $Ex_{le}>0$, critical loads are exceeded; for $Ex_{le}\le 0$ we have non-exceedance. Since nitrogen sinks cannot compensate sulfur acidity, the maximum critical load of sulfur is given by

$$CL_{max}(S) := BC_{dep} - Cl_{dep} + BC_w - Bc_u - ANC_{le(crit)}$$

which is also called the (potential) critical load of acidity. Furthermore, if $N_{dep} \ge CL_{min}(N) := N_i + N_u$, all deposited N is consumed by N sinks and sulfur can be considered alone. Finally, the maximum critical load of nitrogen ($S_{dep}=0$) is given by $CL_{max}(N) := CL_{min}(N) + CL_{max}(S)/(1-f_{de})$. Note, that Ex_{le} is in general not the amount by which to reduce N and/or S deposition to reach non-exceedance (see Section 3.4)

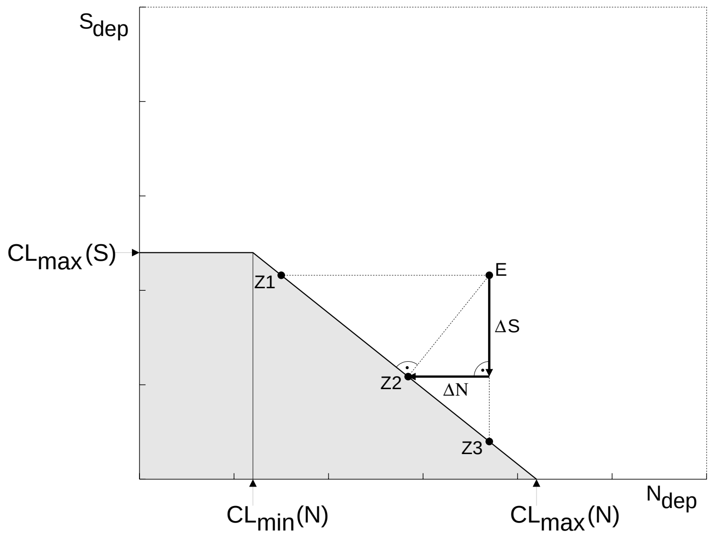

Figure 3 Example critical load function of acidifying N and S (Ex_{le}=0; thick line). The grey-shaded area delineates the pairs of N_{dep} and S_{dep} for which there is non-exceedance (Ex_{le}<0). Also illustrated is the way how the exceedance (AAE) is calculated (see Section 3.4).

Critical loads - $CL_{max}(S)$ and $CL_{max}(N)$ - depend on the temperature T (K) via the weathering of base cations:

$$BC_w(T) = BC_w(T_0)\exp(A/T_0 - A/T)$$

where T_0 is a reference temperature and A=3600K; and they depend on the percolation flux (precipitation minus evapotranspiration) Q (m/yr) via the ANC-leaching term:

$$-ANC_{le(crit)} = Al_{le} + Q^{2/3}(Al_{le}/K_{gibb})^{1/3} \quad \text{with} \quad Al_{le} = 1.5\frac{Bc_{dep}+Bc_w-Bc_u}{(Bc/Al)_{crit}}$$

where $(Bc/Al)_{crit}$ is the critical molar base cation to aluminum ratio, linking soil chemical changes to a 'harmful effect' (increased risk of damage to fine roots). We use the most common value of $(Bc/Al)_{crit}$=1mol/mol (Sverdrup, Warfvinge, 1993).

Summary of New Developments Since First Progress Report

The database needed to calculate critical loads has been updated and extended, and it now covers the same area as the European window of the IMAGE model. Also, the consistency between impact calculations in IMAGE and the critical load calculations has been improved. Finally, the relevant output of new scenarios has been installed in the (soft-linked) assessment framework for ecosystem impacts.

Future Work

Future work will concentrate on two items: (a) to incorporate the change in base cation and nitrogen uptake by vegetation due to climate change. The changes in NPP under the different scenarios, as computed by the IMAGE model, will be used to scale present day uptake; and

(b) the change in (potential) land cover, as computed by the IMAGE model, will be used to modify present land cover (forest type) which has implications on the critical load values.

2.4 Critical Levels and Their Dependence on Climate Change

Purpose of this Task

The purpose of this task is to identify an effective way to simulate the potential impact of varying climate conditions on the direct effects of air pollutants on vegetation. A framework is developed for that purpose that can be used to organize the available quantitative information on the response of different species.

Significance of this Task to Policy and Science

This task contributes to the understanding of the effect of climate on the response of plants to air pollution. This is a complex and important problem where there is an interplay of many processes from very short term episodes to long term trends. The development of large scale models provides a good ground to summarize current knowledge and identify the main sources of uncertainty.

As a supplement to critical loads of acidity, the concept of critical levels is an important tool for taking into account environmental impacts in the current negotiations of a revised N protocol (multi-pollutant multi-effects protocol) in the LRTAP framework. So, from the policy perspective it is of special interest whether climate change will affect critical levels and thus the expected benefits of present air pollution policy.

Analysis to Date

This task has developed an computational framework to investigate the impact of climate changes on the direct intake of air pollutants by plant tissues in different ecosystems. The current version of the model describes in a very simplified way the impact of climate variables on stomatal conductance, that is, the intensity of the flow from the atmosphere to the cells inside the leafs.

The model computes monthly values of stomatal conductance for several kinds of land cover as a function of climatic and soil variables. The calculations rely on response functions of stomatal conductance to light, temperature, water pressure deficit, soil water status and CO_2 concentration. These response functions have been obtained from the literature (Fowler, et al., 1997).

For water soluble pollutants such as SO_2 and NO_2 and NH_3 it is reasonable to consider that the flow of water vapor from the atmosphere to the plant interior (which the stomatal conductance indicates), is proportional to the flow of any of those pollutants. Then if we denote

$X_{crit}(P,LCT)$	as the critical atmospheric concentration level of pollutant (P) for the landcover type (LCT) as agreed to by technical committees of the UN-ECE (United Nations Economic Commission for Europe), and
$G_{H2O}(x,y,LCT,1990)$	as the stomatal conductance (mmol m^{-2} s^{-1}) for grid (x,y), landcover type (LCT) and the conditions prevailing in 1990 as computed by the model

Then the so-called *Reference Flux* F_{ref} can be calculated from the stomatal conductance in 1990 and the critical atmospheric concentration as follows:

$$F_{ref}(x, y, LCT, P) = G_{H2O}(x, y, LCT, 1990) \cdot X_{crit}(P, LCT)$$

This simple approximation gives the reference flux F_{ref}(x,y,LCT,P) that would be associated with the critical atmospheric concentration level under 1990 climatic conditions for a given type of landcover. This reference flux is then used to calculate the *modified critical limit* X_{crit}' for which the reference flux under varying climate scenarios would not be exceeded:

$$X'_{crit}(P, LCT) = F_{ref}(x, y, LCT, P) / G_{H2O}(x, y, LCT, t) \cdot$$

Where $X_{crit}'(x,y,P,LCT,t)$ is the critical monthly atmospheric concentration in year t of pollutant P in grid (x,y) for which the reference flux would not be exceeded, given the stomatal conductance in year t. This value is then compared with the estimated concentrations to calculate the exceedances for that month.

Summary of New Developments Since First Progress Report

The model has been run successfully in all its steps including the comparison with estimated atmospheric concentrations to establish exceedances. There are of course many points in which the model and the calculation procedure can be improved. The overall results seem to indicate that the impact of climate change is smaller than the potential impact of air pollution abatement strategies, and consequently that these make sense under any climate scenario.

Future Work

In the next months several new scenarios will be processed. The conductance model will be improved in some of its key shortcomings, the vapor pressure deficit modulation and the CO_2 impact which are both taken into account in very crude ways. The display and analysis of results will be further developed on the next model runs.

2.5 Critical Climate

Purpose of this Task

The purpose of this task in the AIR-CLIM project is to define a transparent concept of critical thresholds for climate change that allows an analysis of the consequences of climate change under different scenarios for Europe that is consistent to the analysis of regional air pollution with the critical levels/loads concept.

Significance of this Task to Policy and Science

Within AIR-CLIM we developed the critical climate approach that provides new insights of ecosystem sensitivities within Europe with respect to climate change. The approach builds on the critical levels and loads concept, which is frequently used in science and policy to assess the ecosystem sensitivity to regional air pollution. By using similar concepts it becomes feasible to integrate the assessment of two major environmental problems in a single framework. Furthermore, it provides the opportunity to compare sensitivities under various

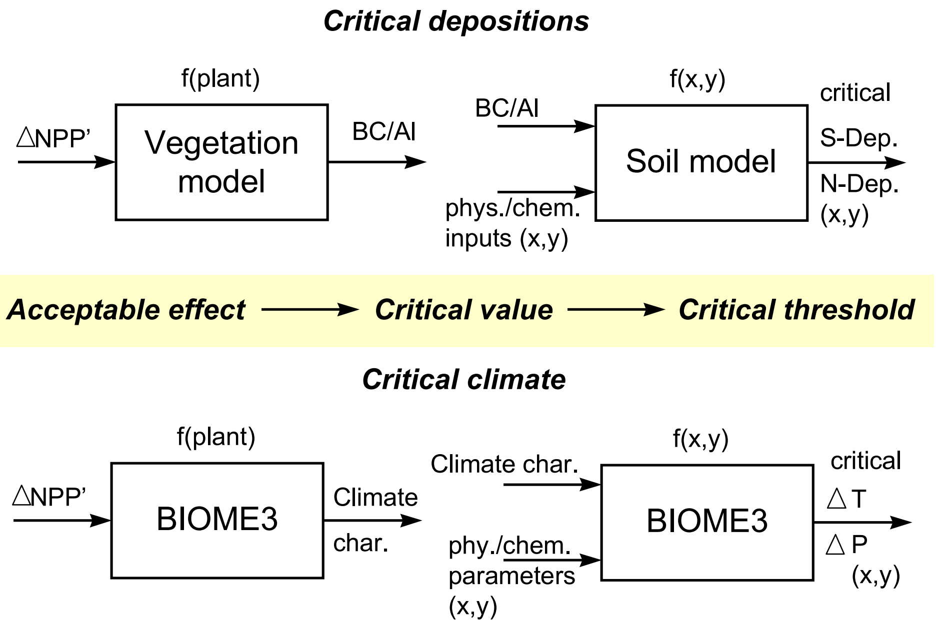

Figure 4 The two step approach to derive critical levels/loads and critical climate

environmental conditions and to examine the effectiveness of different policy control measures.

Analysis to Date

General concept. The critical climate approach is developed within AIR-CLIM to assess negative impacts of climate change. Various recent studies addressed different possibilities of a 'critical climate', although without giving a clear definition (e.g. (Parry *et al.*, 1996), (Leemans, Hootsman, 1997)). We define 'critical climate' as *a quantitative value of climate change, below which only acceptable long-term effects on ecosystem structure and functioning occur according to current knowledge*.

The critical climate approach within AIR-CLIM is an equilibrium approach that assesses long-term effects of climate change on the production (NPP) of natural ecosystems. In our opinion assessing climate change effects on natural ecosystems within Europe is relevant because of the small adaptation potentials of ecosystems and their policy relevance. The critical climate approach integrates the consequences of both changes in temperature and precipitation. Climate Isoline Diagrams (CID) are introduced as two-dimensional diagrams for this purpose. The diagrams depict the allowable changes in temperature and precipitation for a predefined acceptable NPP loss percentage.

The critical climate approach is developed as a parallel to the critical levels/loads concept and derives the critical thresholds in two main steps (Figure 4). First, an *acceptable effect* (NPP loss) is defined from which a *critical value* is derived. Secondly, a *critical climate change* (a combination of temperature and precipitation) is calculated based on the critical value.

Consistencies of critical climate approach with critical levels/loads approach. Both the critical levels/loads and critical climate approaches are equilibrium approaches that take into account the production loss of natural ecosystems. Furthermore, the critical levels/loads and critical climate concepts both use a predefined acceptable NPP loss (based either on laboratory experiments or model calculations) to define a critical threshold for regional air pollution and

Box 1 The BIOME3 Model

BIOME3 ((Haxeltine, Prentice, 1996), 1996) is an equilibrium model that combines biogeography (i.e. vegetation distribution) and biogeochemistry (i.e. ecosystem functioning). Model inputs are latitude, soil characteristics, and climate (i.e. sunshine, precipitation and temperature). The model uses first a set of ecophysiological constraints to determine whether a group of species or so-called plant functional types (pft) may potentially occur in a grid cell. The carbon and water cycle are dynamically integrated in BIOME3. The integrated carbon and water sub-model compute in the second step for each possible pft, what the leaf area index (LAI) would be to maximize the potential net primary production (NPP), considering that the NPP must be sufficient to maintain the LAI. Competition between pfts is included by using the optimum NPP rates as an index of competitiveness. Comparison of the BIOME 3 results with mapped vegetation distribution and NPP measurements has shown good agreement. The model is therefore a suitable tool for an integrated analysis of climate change impacts on ecosystem structure and functioning.

climate change, respectively. Finally, both approaches consist of two steps, by which the acceptable NPP loss is inversely translated into a critical threshold (Figure 4). A difference between the two approaches is that the critical loads of acidity are defined by two independent variables (nitrogen and sulfur) while the critical climate values are defined by two correlated variables (temperature and precipitation).

We consider a critical climate approach analogous to critical levels/loads as most useful, because:

1. critical levels and loads have already earned a measure of acceptance by both scientists (e.g. (De Vries *et al.*, 1995)) and policy makers (e.g. (Gregor *et al.*, 1996)).
2. a harmonized approach enables a comparison of the effectiveness of different environmental policies with respect to both climate change and regional air pollution.

Deriving the critical climate. Three steps can be distinguished in the critical climate approach. In the first step the NPP rates are computed for all 0.5° x 0.5° grid cells in Europe (about 3800 grid cells) for various combinations of temperature and precipitation. The NPP rates are calculated with the BIOME3 model (Haxeltine, Prentice, 1996) (see Box 1 for further details of BIOME3) using a new climate data set for monthly surface air temperature, precipitation and sunshine (New *et al.*, in press-a). Thereby, we varied the current climate values in a step-wise manner:

- for precipitation the current rates are multiplied by factors from 0.2 to 1.8, in increments of 0.2 (0.2x, 0.4x, etc.); and
- for temperature, values between -1°C to +5°C are added to the current values, in increments of 0.5°C.

Sunshine in each grid is kept constant at current value. The advantage of this approach is that it is scenario and climate model independent and therefore broadly applicable.

In the second step those temperature and precipitation combinations are identified for which the computed NPP losses are within ‘acceptable’ ranges. The combinations are represented in CIDs, which are produced for all European grids. Two types of CIDs emerge, either considering the current vegetation as stable or assuming unlimited migration under climate change. Assuming a stable land cover means that any migration and adaptation of the existing vegetation is allowed. It represents a worst case, since it assumes that plant species are unable to keep up with the rate of climate change. The unlimited migration case, which is often assumed in traditional model exercises to assess climate change impacts (e.g. (Cramer, Leemans, 1993)), explicitly considers a large adaptation potential of the land cover. The two cases constitute extremes and are time and scenario independent. In contrast, a case with an intermediate adaptation potential (as in (Van Minnen *et al.*, submit.)) would not be scenario independent, since the rate of change is relevant in that case.

The third and final step in the critical climate approach is to calculate the exceedance of the critical climate under various climate change scenarios. Details about this step are presented in Section 3.3.

Setting acceptable effects. An essential part of the critical climate approach is to determine what NPP loss is *acceptable*. CIDs are derived from specified acceptable levels. The setting of *acceptable* can only partly be based on science. Desirable policy criteria have to be included as well. As part of this we (i) evaluated criteria as defined for other environmental issues; and (ii) analyzed the NPP variation due to historic climate.

Evaluating literature for existing environmental thresholds showed, for example that a 5% yield reduction is explicitly mentioned as acceptable loss in the definition of critical levels for ozone (Gregor *et al.*, 1996). In addition, analyzing the results of (Sverdrup, Warfvinge, 1993) showed that a base cation/aluminum ratio of 1 (often mentioned as critical value) often results in a growth loss of 10-30%, depending on species and location. To our knowledge, there have been no critical thresholds for climate change (either policy or science based) established so far, although the issue is discussed in different reports and papers.

For analyzing the historic NPP variation the BIOME3 model (Box 1) was applied to a global 1901-1995 climate data set (New *et al.*, in press-b). We determined for each grid cell the frequency (i.e. number of years) for which the NPP reduction exceeds a certain NPP percentage loss. This evaluation showed that during the period 1901-1995 in 41% of European grid cells the NPP was reduced by at least 10% in 10 years or less. In 42 % of the grid cells such a NPP reduction occurred in 11-20 out of the 95 years (Figure 5a). A 20% NPP reduction never occurred in 38% of the European grids, while 50% of the grids showed a frequency of 1-5 out of 95 years (Figure 5b). In geographical perspective, high NPP reductions occurred most often in Northern Europe. In Middle and Southern Europe the frequency of a 10% NPP reduction is often less than 10 out of 95 years.

Based on these findings, a 20% NPP reduction is chosen as upper limit of the *acceptable* NPP loss due to climate change. The lower limit is set to 10% as such a NPP loss occurred relatively often in the period 1901-1995. In our opinion the value should be more close to the 10% NPP loss, because (i) without Northern Europe (which is less sensitive to climate change, see Section 3.3), a 10% NPP loss would show a frequency of less than 11-20 out of 95 years; (ii) the acceptable NPP reduction should not lie outside the natural variability. The 10 and 20% acceptable NPP losses also fit well within the aforementioned ranges, defined for other environmental issues.

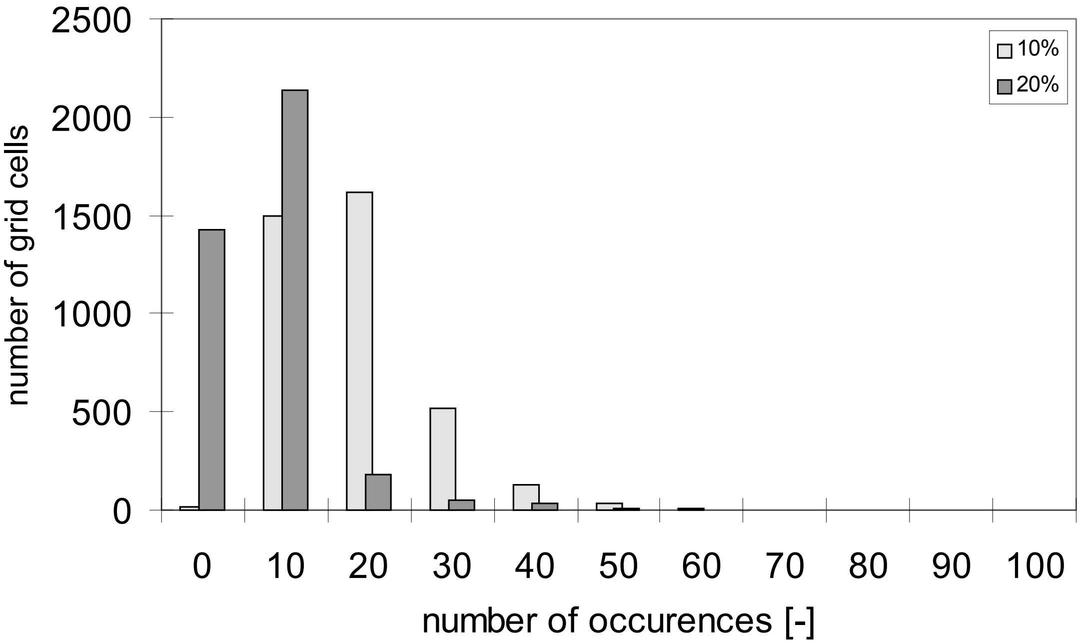

Figure 5 Frequency distribution of years with 10% and 20% reduced NPP rates within Europe, based on BIOME3 application for 1901-1995 climate

Application of the critical climate concept. The critical climate approach consists of the aforementioned three steps. Results of the third step (i.e. evaluating the exceedances of the critical climate under the AIR-CLIM September scenarios) is presented in Section 3.3 and therefore not discussed here. In the first step the potential NPP rates under different climatic conditions are computed for the whole of Europe. Figure 6 illustrates the NPP distribution for current climate. High NPP rates are especially found in Southern Europe due to higher temperatures and longer growing seasons. Figure 7 depicts for two grid cells the NPP responses under different climate conditions. The vegetation in the grid cell in Spain shows a high sensitivity to moisture availability. For 20% of the current precipitation levels the NPP rate drops to about 190 g C/m^2/yr, while it increases to more than 1000 g C/m^2/yr for a 80% increase of precipitation. Temperature increases have only a marginal effect in this grid cell. Accordingly the NPP rates remain more or less constant for a certain precipitation level. In contrast, the vegetation in the Central German grid cell is mainly sensitive to temperature increases for precipitation reductions up to 60%.

The importance of moisture in Southern Europe becomes more noticeable in the second step of the critical climate approach when the NPP information is transferred to the CIDs (Figure 8). We used the aforementioned 10% and 20% as acceptable NPP reductions. Figure 8 shows that three typical responses can be distinguished due to the fact that higher temperatures enhance NPP rates (up to a certain maximum) but also lead to higher evapotranspiration and thus an increased sensitivity to drought:

1. Temperature is the dominating factor in determining the NPP rate. If the precipitation is high relative to the evapotranspiration, temperature gets even an exclusive role (see Northern-Norway, Figure 8). This case mostly occurs in Northern Europe.
2. Moisture availability and thus precipitation becomes more important, although they are still less important than temperature. The direct stimulation of NPP by increasing temperatures overcompensates a potential negative effect due to drought. Thus the critical climate values decrease with increasing temperature (see Southern Finland and Greece, Figure 8). This case is simulated for a large part of Middle-Europe and parts of Southern Europe.

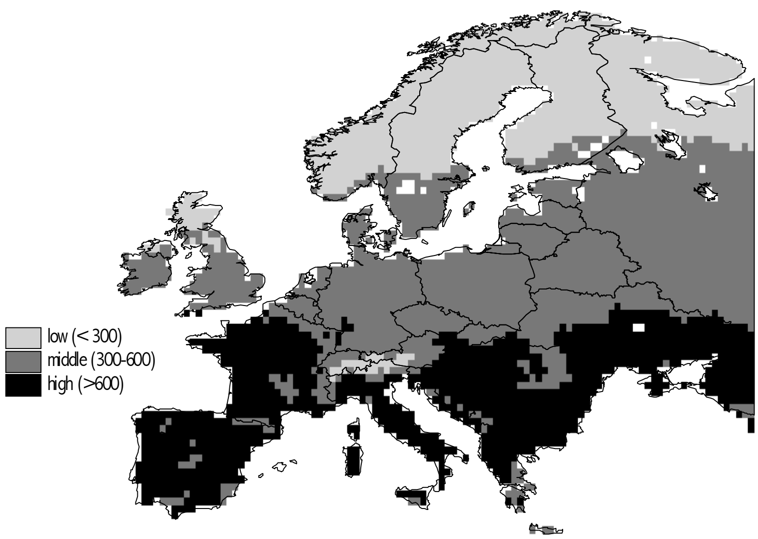

Figure 6 NPP rates [g C/m^2/yr] for current climate (New *et al.*, in press-a), based on the BIOME3 model

1. Increasing temperatures lead in some areas to smaller acceptable precipitation reductions, i.e. increasing critical climate values (see parts of Southern Spain and Portugal, Figure 8). Here, the potential positive effect of higher temperatures on NPP cannot be realized because of lack of moisture.

Figure 9 depicts the two-dimensional critical climate thresholds, assuming an acceptable NPP loss of 10%. It shows the critical temperature changes for two precipitation levels and the critical precipitation change for two levels of temperature change. A large variation of the critical changes in temperature and precipitation can be found, with the sensitive areas in Southern Europe. The critical temperatures change depends on how much precipitation is changed. For current precipitation levels even a 5°C temperature increase does not result in a 10% NPP loss, except for some areas in Spain (Figure 9a). The situation becomes significantly different for reduced precipitation levels (Figure 9b). If the current precipitation is reduced by 40%, temperatures have to be decreased in large parts of Europe to meet the 10% NPP criteria. The critical precipitation change spatially varies (Figure 9c and d): (1) In a large part of Northern Europe NPP of more than 10% only occur if precipitation is reduced by more than 60%, even if the temperature increases by 5°C (Figure 9d). (2) Middle Europe becomes in general less sensitive to reductions in precipitation if the temperature increases. This is caused by the aforementioned direct positive effect of temperature increase on NPP. (3) For higher temperatures Southern Europe becomes even more sensitive to lower precipitation levels.

In summary, most parts of Northern and Middle Europe show a relatively high critical climate value (i.e. relatively large changes in temperature and precipitation are allowed). Northern Europe is mainly sensitive to temperature changes. Increasing temperature values will lead to increasing NPP rates. Middle Europe will also benefit from higher temperature. There, the direct positive effect of temperature on NPP overcompensates NPP losses due to increased drought stress. Only if the temperature increases are accompanied by significant reductions in precipitation large NPP losses occur. Areas with the lowest critical climate values (i.e. with the highest sensitivity to changes in climate) are located in Southern Europe. There, even small temperature rises cause in high NPP losses. The extent of the reduction depends on the precipitation levels.

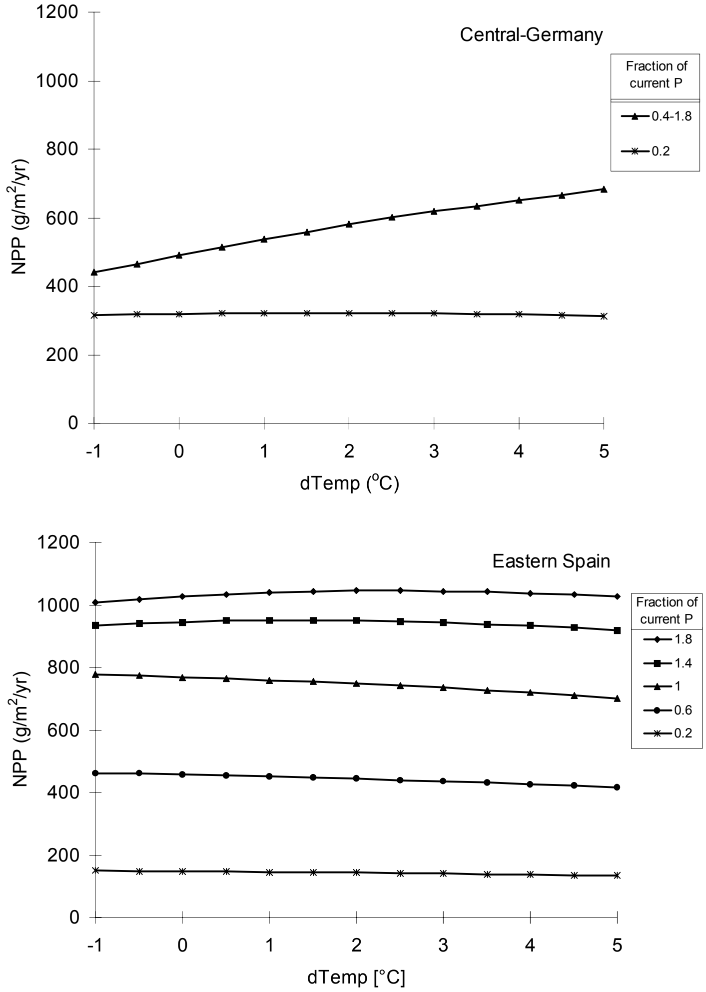

Figure 7 Examples of NPP responses as function of temperature and precipitation at two locations in Europe (temperature and precipitation changes relative to present levels)

Summary of New Developments Since First Progress Report

In the first year of the AIR-CLIM project we developed the basics of the critical climate approach. Since then we built on the developed framework and changed various elements. Firstly, the critical changes in temperature and precipitation are now based on an independent source of information, namely the BIOME3 model. Secondly, we harmonized the critical climate approach with the critical level and load concept. CIDs now depict the sensitivity on grid cell basis rather than country-averages. Two variations of these diagrams are developed, considering different possibilities of adaptation. Furthermore, we focus now on the effects on the production of natural ecosystems, in parallel to the critical level and load approach. Finally, we now set acceptable NPP loss on its historic variation, in addition to an evaluation of criteria as defined for other environmental issues.

Future Work

In the third and final year of the AIR-CLIM project several activities are planned with respect to the critical climate concept. These activities are partly refinements of the existing framework, partly more broader applications.

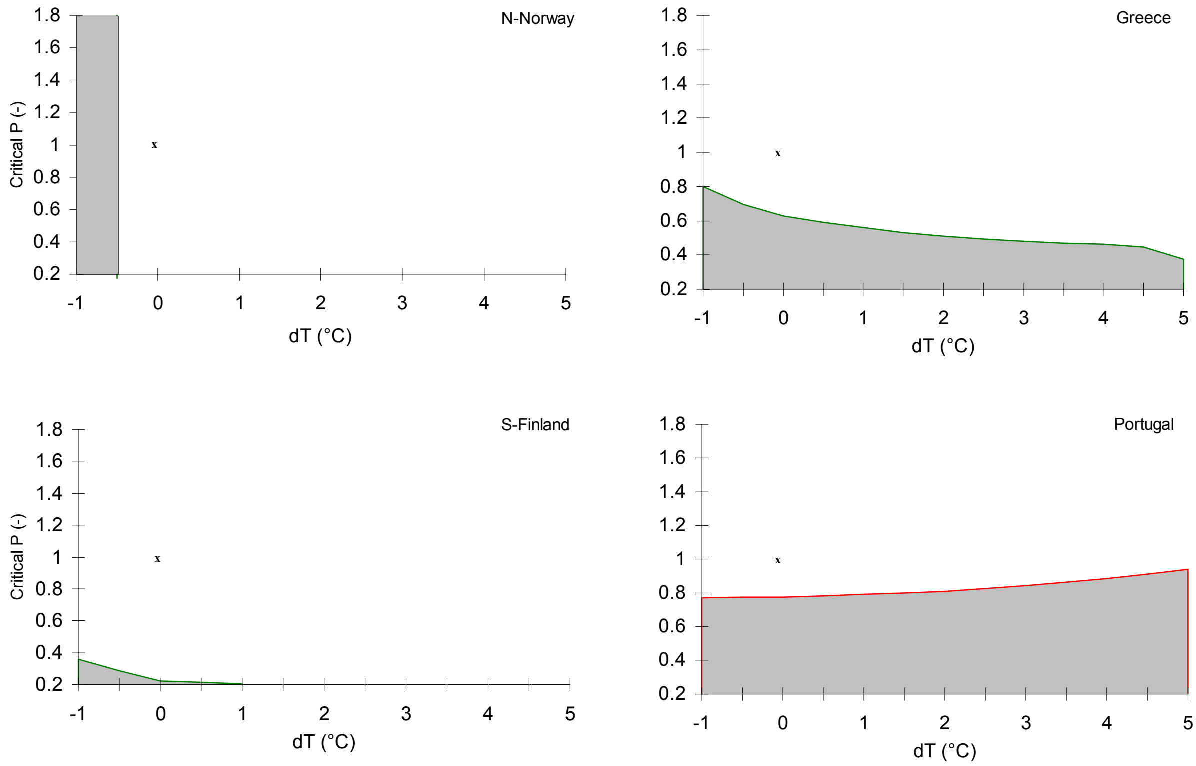

Figure 8 Example of climate isolines diagrams (CID) for different grid cells in Europe (gray area indicate potential exceedance of the acceptable NPP reduction; dT: difference between future and present temperature, dP: precipitation change expressed as multiple of present precipitation)

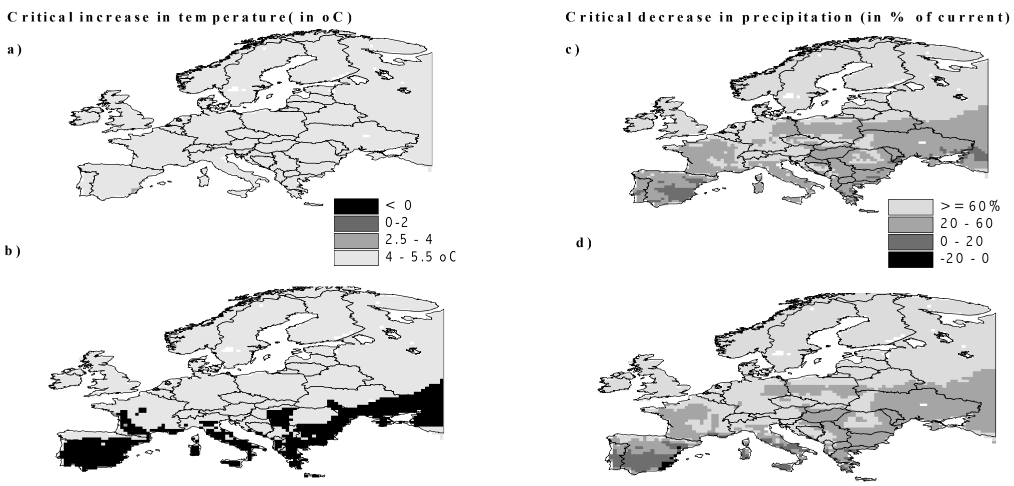

Figure 9 Representation of two-dimension climate thresholds. Critical temperature increases for (a) current and (b) precipitation levels reduced by 40% and critical precipitation changes for (c) current temperature and for (d) temperature increased by 5°C, assuming an acceptable NPP reduction of 10% in all cases

Firstly, CIDs will be developed for the currently known protected areas, in addition to the existing CIDs that depict the sensitivities within the entire AIR-CLIM region. Secondly, the currently defined acceptable NPP losses will be compared to other sources of historic climate and inter-annual NPP fluctuations. Such additional data and model results will give an added value to the applicability of the set acceptable losses.

2.6 Integration of Air Pollution and Climate Change Impacts

Purpose of this Task

The purpose of this task is to look at the interaction of climate change and regional air pollution on the impact level. One aspect, the influence of climate change on critical levels/loads, has been analyzed in Sections 2.3 and 2.4. The integration of climate change impacts and air pollution impacts is covered in this section of the report.

Significance of this Task to Policy and Science

The environmental issues global warming and air pollution have been handled separately in policymaking so far, because, among other reasons, there is no approach available to examine their impacts in an integrated way. Here we present an integrated approach to assess the impacts of global warming and regional air pollution.

From the scientific perspective the approach provides a method for combining disparate information from different disciplines having to do with the environment in an integrated way.

Analysis to Date

In order to harmonize the assessment of climate change and air pollution impacts, we take a hierarchical approach (Figure 10). According to present knowledge one of the most important impacts of climate change could be major shifts of vegetation in Europe (see Section 2.5 for example), but such large-scale shifts are not expected because of air pollution. Thus, the first step of the analysis is to assess the land cover changes due to climate change. Three cases are possible (Figure 10):
(1) the land cover is unchanged and undegraded, or
(2) the land cover is unchanged and degraded, i.e. the NPP is decreased compared to the present situation, or
(3) the land cover is changed.

The second step is to recompute the critical levels/loads under climate change for the new land cover type. The third step is to compute the area in which air pollution exceeds the new critical levels and loads.

Summary of Progress to Date and its Significance

An approach for the integration of climate change and regional air pollution on the impact level has been developed. This approach combines disparate information from different disciplines connected to environmental issues in a semi-unified way. Thus, the approach will support policymakers in looking at these environmental problems in a holistic way.

2.7 Calculation of Reduction Costs

Purpose of this Task

The purpose of this task is to develop, implement and apply a methodology within the IMAGE modelling framework for the assessment of cost-effective emission reduction control

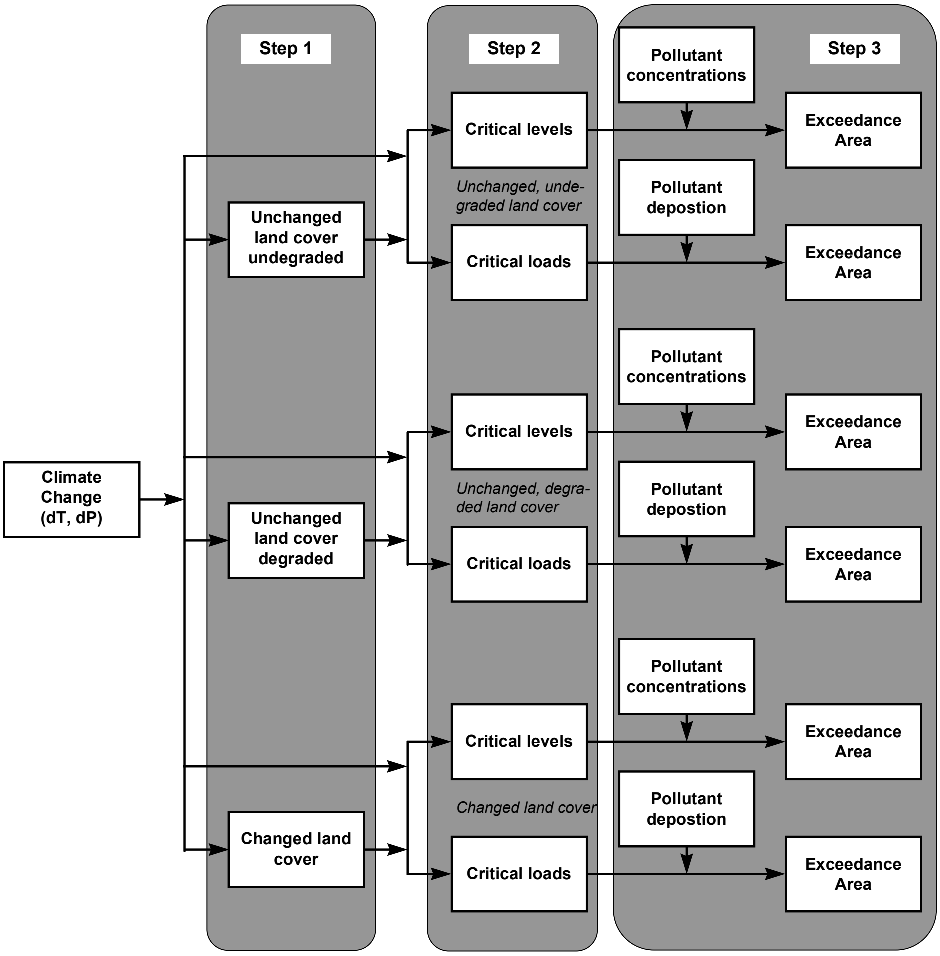

Figure 10 Hierarchical procedure for the integrated assessment of climate and air pollution impacts

strategies for both regional air pollution and climate change. The application of this methodology identifies a joint mitigation strategy for acidifying pollutants and greenhouse gases in terms of abatement options and the differences and avoided costs compared to single non-co-ordinated strategies. The global scale of climate change requires that the analysis will be conducted for all continents. However, the focus of the analysis will be on the European regions, assessing in more detail the regional reduction and effects of air pollution.

Significance of this Task to Policy and Science

Up to now, the development of (international) abatement policies has taken place in separate policy arenas for regional air pollution and (global) climate change. Hence, little integrated research has been conducted on a joint abatement strategy at a global scale which includes those control options that mitigate both environmental problems simultaneously and cost-effectively. It is very well possible that options which are not cost-effective from the angle of single abatement strategy will be cost-effective from the angle of a joint strategy. It is important to address this issue in order to enhance the overall effectiveness of international and long term environmental policies.

Analysis to Date

Mitigation of the main greenhouse gas CO_2 is largely dependent on options resulting in less energy consumption (efficiency and conservation) or a shift in fuel mix to energy carriers that result in less CO_2. By comparison, SO_2 has up to now been mostly abated by add-on technologies such as flue gas desulphurisation (FGD) although a lower energy consumption and a shift to energy carriers with a low sulphur content such as natural gas or renewables also reduce SO_2 emissions.

To tackle a combined mitigation of climate change and regional air pollution, a global model that covers both greenhouse gases and acidifying substances including their underlying activities and technologies is needed. The IMAGE 2.2 model will need several extensions in order to fulfil such requirements.

First, the emission module which calculates emissions from energy combustion and industrial processes has to be updated and extended in order to represent add-on mitigation options in terms of costs and reduction potentials. This concerns mainly SO_2 and NO_x reduction options.

Second, the energy-industry module of IMAGE 2.2, called TIMER has to be updated with respect to the level of technological detail in order to be able to analyse mitigation options for both climate change and regional air pollution at a regional scale.

Third, some methodological developments will be needed in order to be able to identify a cost-effective emission reduction strategy for both climate change and regional air pollution. Since IMAGE / TIMER is not an optimisation model nor a market driven equilibrium model, but a complex simulation model, the focus will be on developing calculation algorithms for finding cost-effective solutions for given (overall) scenario objectives.

After these extensions of TIMER, cost-effective emission reduction strategies for both greenhouse gases and acidifying substances can be analysed in the context of the SRES A1 and B1 scenarios and cases.

In the present project, the most important substances and sources will be considered for contribution to the emission reduction strategy in the form of reduction options. It concerns the most important emissions from energy and industry:

- CO_2 from energy combustion / industrial process emissions and afforestation,
- CH_4 from energy / industry,
- N_2O from energy / industry,
- SO_2 and NO_x from energy / industry.

Emission reduction options relating to non-CO_2 greenhouse gases such as HFC, PFC, SF_6 and acidifying substances such as NH_3 and SO_2 from nature will not be included in this project.

At present, a pilot version of the submodule for add-on emission reduction options has been built. This submodule calculates the emission reduction potentials and their marginal costs for each world region for a given scenario and sight year. It is capable of ranking reduction options and potentials according to their marginal costs in the form of a marginal reduction costs curve. This can be used to assess the most cost-effective package of reduction options to meet a given emission reduction objective on a global or regional scale. First results for the mitigation of SO_2 will be presented for the three European regions.

General approach

The present version of TIMER, being the energy-industry module of IMAGE 2.2, calculates for each world region the energy consumption and fuel mix in the different economic sectors. The demand for useful energy is primarily based upon scenario parameters such as population, Gross Regional Product (GRP), Value Added for industry and services, consumer expenditures etc. Also, prices of energy carriers determine the useful energy demand. The fuel mix is determined on the basis of relative prices of energy carriers. These energy prices of secondary fuels are endogenously calculated in the fuel supply submodule (solids, liquids and gas sector) and the electricity generation submodule. The primary energy prices are mainly based upon the costs of exploration, transportation and generation.

The emissions are calculated in a separate Emissions module on the basis of TIMER output data on fossil fuel combustion in the different sectors. These are multiplied with specific emission coefficients for coal, oil and gas (emission factors). Emissions from industrial processes are calculated on the basis of GRP related estimates of activity data and specific emission coefficients. In the present model structure, roughly two types of emission reduction options can be distinguished: add-on technologies and integrated (energy) technologies.

Add-on technology concerns end-of-pipe technologies or desulphurised fuels which do not directly interfere with the energy system. Therefore, these emission reductions and related costs can be calculated separately in the Emissions module. The (costs of these) options are not directly taken into account in the determination of the technology and fuel mix in the energy system. Add-on technologies, potentials and costs are particularly relevant for the assessment of mitigation strategies for regional air pollution. The development of a methodology and its implementation in the Emissions module has been executed in the first phase of this task. This methodology is a commonly used marginal cost approach (for example in RAINS, authoritative acidification model for Europe). It is described in more detail below.

Integrated reduction options, such as efficiency improvements, energy conservation and fuel switch (particularly relevant for climate change mitigation), take place in the heart of the energy system and thus the TIMER module. Reductions and costs of these options are preferably calculated inside the TIMER module since they are strongly related with the rest of the energy system. In the present TIMER version, energy technologies are either explicitly represented in some sectors and implicitly represented (e.g. by energy price elasticity's) in other sectors. If technology is explicitly represented, it can be endogenously calculated (technology implementation based on costs and / or energy prices) or exogenously specified. In both cases the choice of technological options may be limited due to specification at a high aggregation level. Further distinction of energy technologies functioning as integrated emission reduction options should be realised without introducing inconsistencies with the present model approach. This will be described further below.

Cost calculation method for add-on technology

At present, a pilot version of the submodule for add-on emission reduction options is operational. This submodule calculates the emission reduction potentials and their marginal costs for each world region for a given scenario and sight year. It is capable of ranking reduction options and potentials into a marginal reduction costs curve in order to calculate a cost-effective package of reduction options to meet a given emission reduction objective on a global or regional scale. This methodology is in line with the methodology in RAINS used for

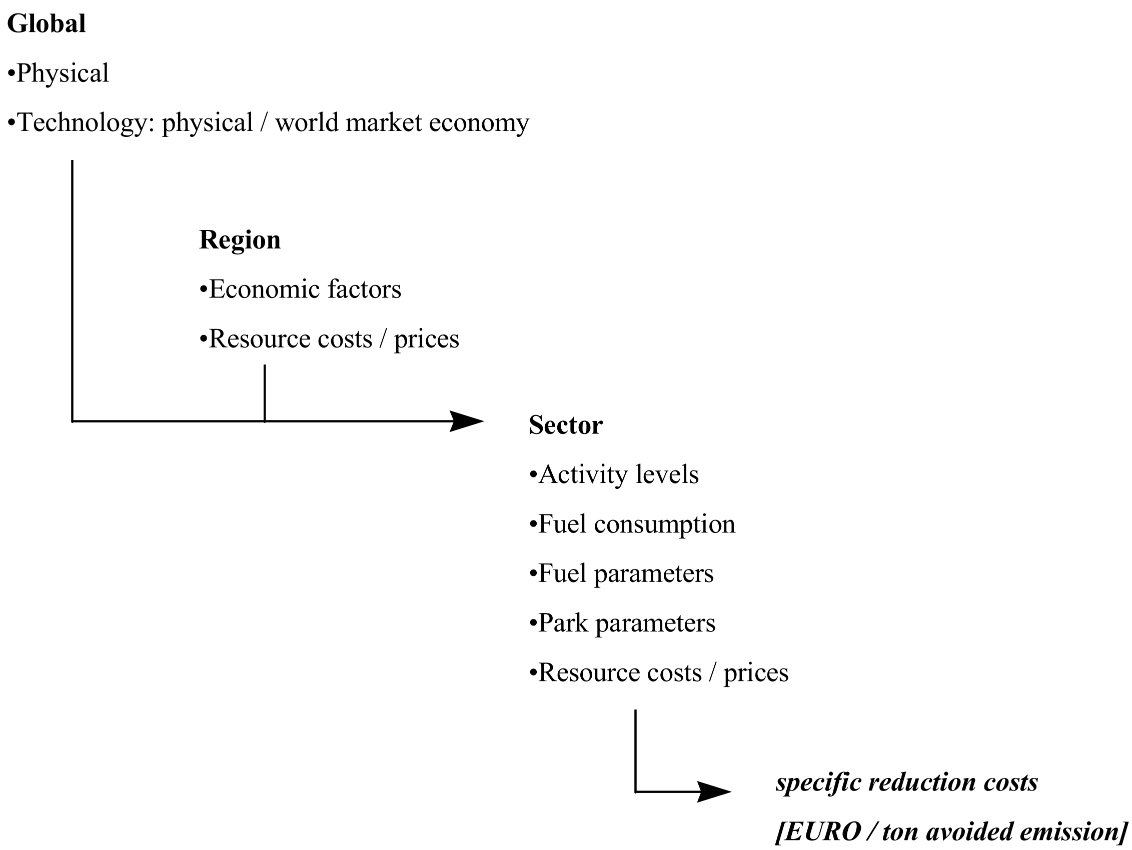

Figure 11 Schematic representation of the emission reduction costs methodology as applied in the pilot Emission module of IMAGE / TIMER

the examination of cost-effective emission reduction strategies. Main differences are that RAINS distinguishes countries instead of world regions and that the cost-optimisation in RAINS is driven by objectives in the form of critical loads instead of emissions, which adds a geographical component to the optimisation. In IMAGE / TIMER the geographical component of acidifying effects is not taken into account in the optimisation process of control options.

The structure of the cost calculation in the Emissions module is schematically presented in Figure 11. Data is specified at different aggregation levels in order to be able to calculate at the most detailed level (sector and fuel) the specific costs per unit of avoided emission reduction and consequently the marginal costs.

Global. At a global level, physical parameters such as relative flue gas volume and mol mass are specified. Also technology parameters characterising technologies available on the world market are specified on global level. It concerns removal efficiency, investment cost function (of average installed capacity or boiler size), lifetime and resource demands (labour, sorbent, disposal and electricity demand).

Region. Region specific parameters concern economic factors and resource costs / prices. These factors account for general (i.e. not sectoral) regional differences in reduction costs. General economic factors include real interest rates and typical retrofit factor and fixed costs fractions, both specified as a fraction of the investment costs. Also a market price factor referring to differences with respect to world market investment costs and a learning rate, referring to the speed with which investment costs will decrease as a result of technological and market development, can be specified. Resource costs and prices refer to the costs of labour, sorbent and disposal in a region. These could be scenario dependent.

Sector. At sector level, activity levels and fuel consumption stemming from TIMER are used as an input for the reduction cost calculation. Also, fuel parameters such as heating value, sulphur content and sulphur retention are used to calculate the fuel specific emission factor before abatement. Park parameters (average installed capacity and full load operation hours) have to be specified for each sector and fuel in order to calculate the investment costs of the reduction technology. Finally, the electricity price for each sector has to be known from TIMER as an input for the cost calculation.

After ranking the marginal reduction costs in a marginal emission reduction costs curve, a powerful means for designing cost-effective emission reduction strategies is available.

Some parameters at regional and sector level, which have to be specified in addition to the IMAGE / TIMER output, are scenario dependent. These have to be specified consistent with the scenario at hand. It concerns:
- labour, sorbent and disposal costs (Region);
- market price factor and learning rate (Region);
- sectoral average installed capacity and full load operation hours (Sector).

For each fuel, sector and region, specific and marginal emission reduction costs in EURO per ton avoided emission and its reduction potential are calculated for each technically feasible reduction option. The reduction potentials and marginal costs are ranked into marginal reduction costs curve(s) which are the basis for designing cost-effective mitigation strategies.

Cost calculation method for integrated options

Integrated reduction options, such as efficiency improvements, energy conservation and fuel switching (particularly relevant for climate change mitigation), take place in the energy system itself and thus the TIMER module. Further distinction of energy technologies functioning as integrated emission reduction options is desirable but should be realised without introducing inconsistencies with the present model approach. In some sectors such as the electricity generation sector, TIMER is taking technology parameters such as efficiency and costs explicitly into account. In these cases, a refinement of the specification or an extension of the number of technologies to choose from would be an obvious solution. In other sectors such as the end-use sectors, technology is represented in an implicit way, using energy price elasticity's. A first order estimation of the costs for end-users would be the price difference which is needed to force the end-user to become more efficient or switch fuels and thus reduce emissions.

A general cost-effective emission reduction strategy could be enforced by using emission taxes on different fuels and technologies in order to have a cost-effective response throughout the TIMER module and the Emission reduction module. Different greenhouse gases should be weighted by use of Global Warming Potentials. When both greenhouse gases and SO_2 and NO_x have to be reduced in a joint strategy, shadow prices have to be used to find the cost-effective solution.

The methodology will be further during year 2000. The next paragraphs present the current methodology used in TIMER.

Fuel supply. The fuel supply submodules are all three (solid fuel, liquid fuel and gaseous fuel) based upon a conceptual scheme in which resources are discovered through exploration, produced through exploitation and converted into secondary fuels. The costs are determined by the simultaneous process of depletion and learning-by-doing. The latter is based upon a loglinear learning function, the former on exogenous depletion multipliers. For liquid and gaseous fuels, there is a biomass-derived alternative which penetrates the market once its relative costs are competitive. Interregional fuel trade is calculated on the basis of relative costs differences and an estimate of transport costs as a function of distance.

Electricity generation.The electricity generation includes hydropower, non-fossil (nuclear and renewables) and different fossil fuels. Hydropower is installed according to an exogenous, time-dependent fraction of the hydropower potential. The remaining electricity production necessary to meet the electricity demand is allocated to non-fossil and fossil fuels on the basis of relative generation costs which depend on fuel specific investment costs, conversion efficiencies and fuel prices. Non-fossil investment costs decrease loglinearly with the cumulative production (a learning curve). Further, the mix of different fossil fuels is also calculated by the relative generation costs. Generation costs plus additional transmission and distribution costs make up the electricity price for consumers.

Energy demand. The energy end-use demand for heat and electricity is calculated from sectoral activity levels modified by exogenous and price induced efficiency improvements. The use of secondary fuels and electricity is calculated by multiplication with time-dependent fuel conversion efficiencies. The mix of secondary energy carriers is dependent on end-use prices, including price adders to reflect taxes and subsidies. Such premium factors can also reflect considerations on security, user convenience, environmental side-effects and lack of infrastructure.

Regional and temporal differentiation

A short analysis of cost parameters of add-on reduction technologies indicated that the most important differences in costs between regions are caused by differences in the following region and sector specific parameters:

- real interest rate;
- energy consumption level;
- fuel mix and quality;
- park properties (operation hours and average installed capacity).

Especially with respect to the last point, the scenario storylines have to be completed with assumptions on the park developments. Costs of sorbents, disposal and labour for operation and maintenance are of less importance in the present situation. More research is needed on regional differentiation of the underlying labour costs included in the investment costs and retrofit factors and fixed cost fractions.

One can pose the question whether these regional differences will be preserved under the scenario assumptions taken, or that these differences gradually will diminish and disappear as a result of global convergence processes. One approach to deal with this in a more systematic way is the application of learning curves. These learning curves are simple loglinear functions that describe the development of a parameter, e.g. the investment costs, as a function of a relevant variable, e.g. the cumulative installed capacity. These loglinear learning curves are already applied for temporal development of investment cost of non-fossil electricity generation in TIMER.

Besides this combination of regional and temporal differentiation, it is important to have an impression of the general development in time of the most important technology cost parameters. It is important for economic reasons (not only costs, but also in terms of economic burden), as well as for comparison of technological options (the cost-effectiveness of options can develop differently). The most important factor in this respect is the investment costs. Generally, this is handled with a loglinear learning curve. For some technologies, this is already present in TIMER. This has to be examined in more detail, especially with respect to methodological consistency.

It would be interesting to be able to downscale regional results to national level since many environmental policies are decided at the European level. However, this was not planned within the current study since it would require an enormous effort in itself.

Scenarios and Cases

Here we present an overview of the scenarios and cases for the assessment of emission reduction costs of different mitigation policy strategies, in particular the avoided costs of a joint abatement policy strategy for regional air pollution and climate change.

For the A1 and B1 scenarios (see Section 3.1), a number of cases will be calculated:

- **Baseline case:** no climate change policy and Pre-99 SO_2 and NO_x policies,
- **Regional air pollution case:** Post-99 SO_2 and NO_x policies,
- **Climate change case:** GHG policies (450/550 ppm),
- **Combined case:** GHG policies (450/550 ppm) and Post-99 SO_2 and NO_x policies.

By means of this systematic design of cases, the abatement costs of separate, non-co-ordinated acidification and climate change policies can be compared with a joint policy for acidification and climate change (combined case). This comparison gives an indication of the costs avoided by the joint strategy.

In all cases, emission objectives for the different regions will be imposed top-down on the model, which has to meet this objective by means of the implementation of a cost-effective package of reduction options. In this analysis the Pollutant Burden Approach is used to describe how European policy objectives for regional air pollution are used to define emission objectives for regional air pollution in other world regions.

The timing of objectives and the emission reduction options and costs will be very important. The ‘strength’ of the target of one single policy or the combination of policies will determine whether integrated or joint strategies will be followed immediately or only the long term. ‘Lock-in’ effects or bifurcation points will not be assessed accurately by TIMER since stock accounts of installed capacity is not present in the model.

As a first estimate, policy objectives are defined in terms of emission or concentration levels. It is, however, not clear whether reaching the emission objective will result in the effect that was foreseen when the emission target was negotiated. One can assume that the targets were negotiated in absence of knowledge on the ‘other air pollution problem’.

The fact that the policy for regional air pollution will be intensified due to the multi-pollutant protocol (Gothenburg 1999) will result in lower levels of SO_4 aerosols, herewith decreasing the acidifying effect and the cooling effect. It is possible to back-calculate the (lower) greenhouse gas emission levels required to meet the ‘originally foreseen’ climate change effects. The additional efforts to meet these emission levels can be assessed and expressed in terms of additional costs.

Summary of Progress to Date and its Significance

At present, a pilot version of the submodule for add-on emission reduction options has been built. This submodule calculates the emission reduction potentials and their marginal costs for each world region. It is capable of ranking reduction options and potentials according to their marginal costs in the form of a marginal reduction costs curve. This can be used to assess the most cost-effective package of reduction options to meet a given emission reduction objective on a global or regional scale. The pilot version has been applied to generate the first results for the mitigation of SO_2 for the three European regions. Data have been collected for SO_2 and NO_x reduction technology. This means that the calculation of cost-effective SO_2 and NO_x emission reduction strategies for all world regions and scenarios is within reach.

Climate change options are already included to a certain extent in the TIMER module of IMAGE. The extended specification of greenhouse gas emission reduction options as well as the automatic generation of cost-effective multi-pollutant reduction strategies will involve methodological changes which will be addressed within the next 4 months.

Future Work

In the next year of the project it is planned to:

- harmonise and compare base year emissions and emission factors for different fuel categories of RAINS and IMAGE;
- investigate the application of reduction options to shares of fuel consumption in case of a higher aggregation level of fuels (e.g. heavy oil versus diesel);
- include present policies in the baseline scenarios;
- extend the SO_2 reduction options to other regions;
- collect the data on reduction options and costs (NO_x and GHG abatement);
- develop scenario consistent assumptions for regional and temporal differentiation;
- develop a methodology to improve the cost calculation of integrated reduction measures in TIMER;
- develop a calculation algorithm to design cost-effective reduction strategies for multiple pollutants, covering both integrated measures in TIMER and add-on methodology in the Emissions module;
- develop a methodology for temporal differentiation;
- implement the methodologies in TIMER / IMAGE;
- run and analyse scenarios and cases;
- report the results.

3 ANALYSIS OF SEPTEMBER SCENARIOS

Purpose of this Task

The framework for the final set of AIR-CLIM scenarios is developed and a preliminary assessment of the scenario set is carried out.

Significance to Policy and Science

The cooling effect of sulfur aerosols on climate was one of the most important that changed the scientific assessment of global warming in the last decade. While this factor is now routinely included in scientific assessments, other aspects of the interaction of climate change and air pollution have not been closely studied. We expect that the scenario analysis carried out in the AIR-CLIM project will contribute to the scientific understanding of this interaction.

The negotiations of climate change and air pollution policy relies heavily on the analysis of scenarios. The purpose of the final AIR-CLIM scenario analysis will be to provide integrated information on both environmental problems. This information will help to integrate the two issues in the policy process.

3.1 Definition of September Scenarios and Emissions

For the 3rd scientific assessment of the Intergovernmental Panel on Climate Change (IPCC) the plenary session of the IPCC has charged Working Group III of the Panel to develop a Special Report on Emissions Scenarios (SRES), including a new set of scenarios for the emissions of greenhouse gases. The scenarios are 'non-intervention scenarios', implying that no explicit additional climate policies are to be assumed i.e. the Kyoto Protocol is *not* taken into account. Four sets of qualitative storylines describing possible futures were developed (see Table 2), and quantification of these storylines in terms of energy and land-use emissions derived, based on the modeling work of six different groups, one of them the IMAGE team at RIVM.

In this report results will be presented for the so-called *September scenarios* that are a sub-set of the final AIR-CLIM scenarios (see Table 3 for an overview). Start scenarios for the September (and the final) scenarios are the A1 and B1 scenarios of the SRES scenarios as realized in the TIMER/IMAGE model. The A1 storyline describes a future world of rapid

Table 2 Characterization of the four SRES scenarios (the scenarios in *italics* are used in the AIR-CLIM project)

	'open' world with high degree of global governance (globalization)	'closed' world with cultural, technical and economic pluralism
limited, free-market orientation on environmental and social issues	*A1*	A2
strong and explicit orientation on sustainability and equity issues	*B1*	B2

Table 3 Characterization of the AIR-CLIM September scenarios. Impact analyses are presented in this report only for the scenarios in *italics*.

	Start scenario	GHG policy	SO_2/NO_x policies
A1-SR	*A1*	*None*	*Pre-99*
A1-SA	A1	None	Post-99
A1-550-SA	A1	To achieve 550 ppm stabilization	Post-99
B1-SR	*B1*	*None*	*Pre-99*
B1-450-SA	*B1*	*To achieve 450 ppm stabilization*	*Post-99*

introduction of new and more efficient technology. Major underlying themes are convergence, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The B1 storyline describes a convergent world with rapid change in economic structures toward a service and information economy, reduction in material density ('dematerialization') and introduction of clean and resource-efficient technologies. The emphasis is on global solutions to environmental and social sustainability.

Driving forces of the scenarios are population and GDP. The population development in the A1 and B1 scenarios are identical, peaking at 8.7 billion in 2050 and then decreasing to 7.1 billion by 2100. The economic development, however, differs significantly. In A1 the global GDP increases from $2.7 \cdot 10^{16}$ US-\$ in 1990 to $5.8 \cdot 10^{17}$ US-\$ in 2100 while in B1 the global GDP reaches only $3.5 \cdot 10^{17}$ US-\$ in that year. Global primary energy use increases in A1 up to about 750 EJ in 2100 and for B1 up to about 350 EJ in the TIMER realization of these scenarios. For the A1 scenario the global CO_2 concentration reaches 740 ppm in 2100, for B1 540 ppm.

The September mitigation scenarios (A1-550-SA and B1-450-SA) are so-called stabilization scenarios i.e. scenarios in which the CO_2 concentration is stabilized at a certain level. For A1 mitigation measures are assumed for which the CO_2 concentration stabilizes at 550 ppm; for B1 the respective level is 450 ppm. Examples for the mitigation measures assumed are government subsidies for energy efficiency measures, carbon taxes on secondary fuels, or stimulation of high-efficiency gas-based and non-fossil options for electric power generation. Figure 12 shows the development of the global CO_2 *equivalent* emissions for the September scenarios.

A1 and B1 do not assume any climate policy but rather stringent SO_2 policies. In a first step, these stringent SO_2 policies are removed and 'AIR-CLIM' policies introduced to derive the reference scenarios A1-SR and B1-SR (SR for Sulfur Reference) for AIR-CLIM. Thereby, two policy sets are distinguished:

(1) *Pre-99 SO_2/NO_x policies* refer to emission reductions agreed on before or earlier than 1999. Thereby the following assumptions are applied:
- SO_2 and NO_x in Europe (incl. former USSR):
  - until 2010 following 1994 Sulfur Protocol and 1988 NO_x Protocol,
  - after 2010: the emissions are capped by the 2010 emissions as fixed in the protocols;
- SO_2 outside Europe:
  - Reduction starts when the 'pollutant burden' in non-Protocol regions reaches the same magnitude as the pollutant burden of industrialized regions at the time when they began to reduce their emissions.

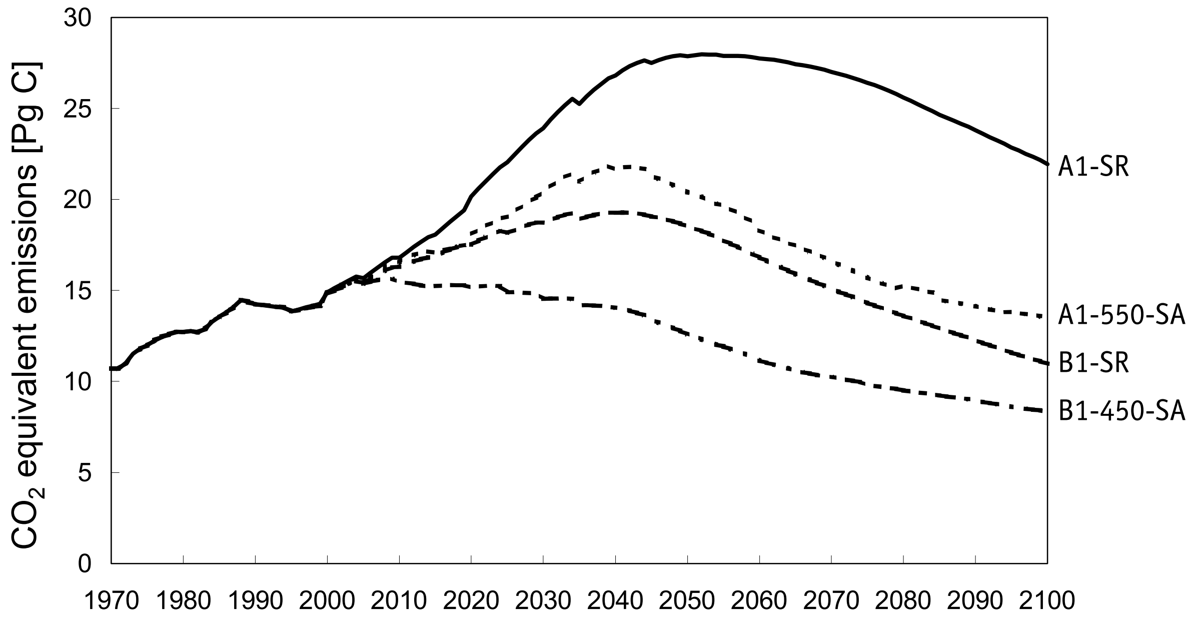

Figure 12 Development of the global CO_2 equivalent emissions for the September scenarios

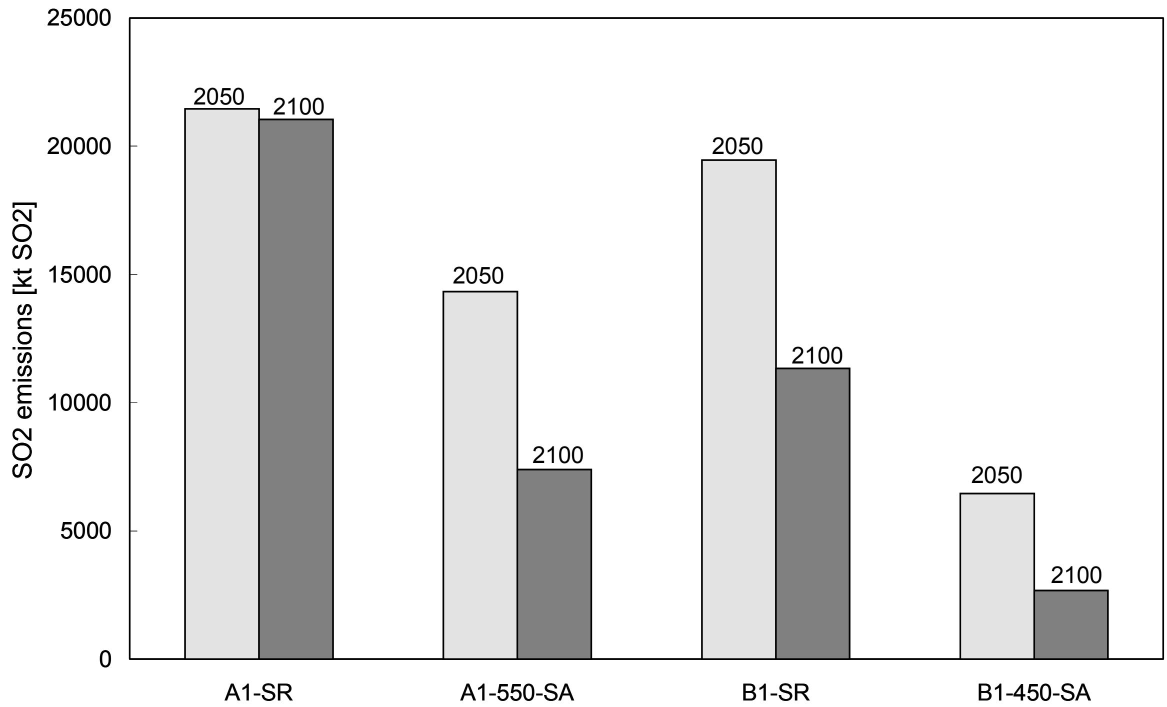

Figure 13 Development of the European SO_2 emissions for the September scenarios

- After reduction start the reduction rate follows the past European development up to the approximate reduction level of the 1994 Sulfur Protocol

(1) *Post-99 policies*: The development of the overall reduction of the SO_2 emissions is exogeneously set in TIMER based on expert judgment. This is not consistent to the derivation of the pre-99 policies. Notwithstanding, the Post-99 scenarios (A1-550-SA and B1-450-SA) are used here as they are the mitigation scenarios developed for IPCC by the IMAGE group. The inconsistency in deriving Post-99 and Pre-99 policies will be remedied for the final AIR-CLIM analysis.

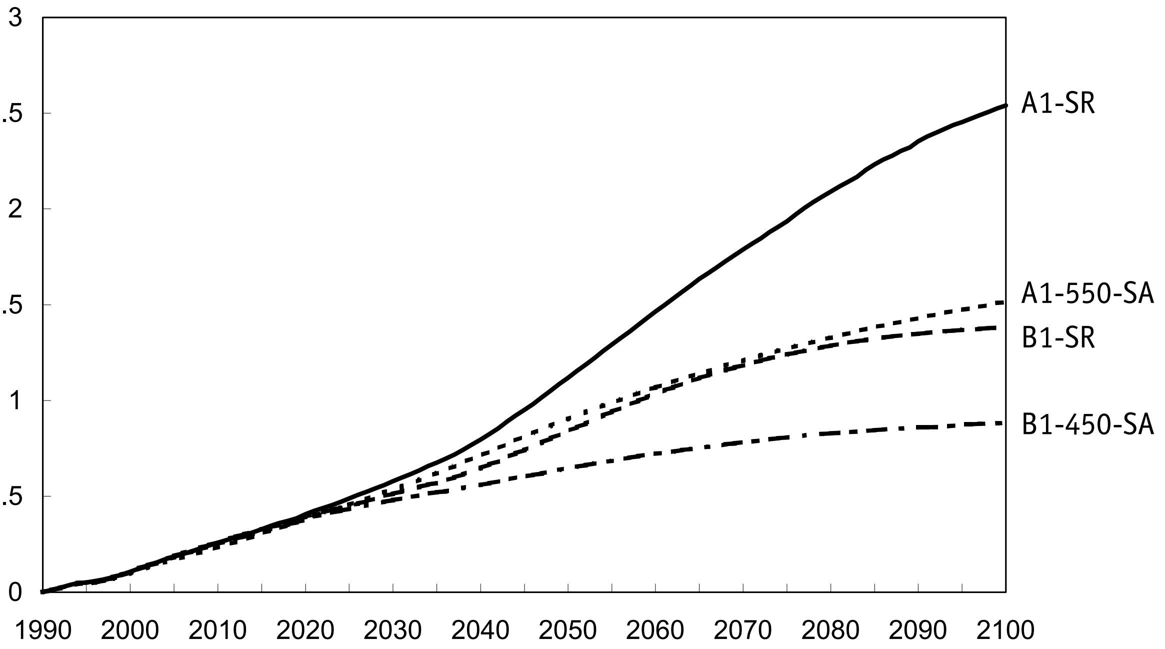

Figure 14 Global temperature change [°C] relative to 1990 for the September scenarios

> In the long-term the present post-99 policies are more stringent than the pre-99 policies but for some regions the SO_2 emissions are higher in the short-term. However, this does not affect the results for the later reference years presented in this report.

Figure 13 shows the development of the European SO_2 emissions. While the emissions in the A1-SR scenario stay on the 2010 level, in the B1-SR scenario they drop without further increase in the reduction rate due to a decrease in energy consumption. The pattern is similar for the NO_x emissions in Europe with the exception that for NO_x the B1-SR emissions are in the end below the A1-550-SA emissions. Thereby it should be kept in mind that the A1 and the B1 scenarios are based on different storylines i.e. in A1 about double as much primary energy is used as in B1.

The European NH_3 emissions are calculated by multiplying activity levels computed by IMAGE (e.g. livestock population) with constant emission factors (for a further description see the first AIR-CLIM progress report (Mayerhofer *et al.*, 1999)). For A1-SR and A1-550-SA the European NH_3 emissions remain on a level of about 6500 kt for the whole time period under analysis while for B1-SR and B1-450-SA the level decreases after 2020 to about 4500 kt in 2100.

3.2 Global and Regional Climate Change

IMAGE 2.1 runs have been carried out for the September scenarios described above yielding temperature and precipitation changes on a 0.5x0.5° grid and land cover changes. For A1-SR the realized global temperature in 2100 will be 2.8°C higher than in 1990 (Figure 14). For the other scenarios the temperature increase will be much less: 1.8°C for A1-550-SA, 1.7°C for B1-SR and 1.2°C for B1-450-SA.

Table 4 Exceedance areas for 2050, 2075 and 2100 for the two adaptation cases and 10% and 20% acceptable NPP loss (as % of the total AIR-CLIM area)

Case:	Exceedance area, 10% NPP loss			Exceedance area, 20% NPP loss		
Unlimited migr.	2050	2075	2100	2050	2075	2100
A1-SR	3.6	11.4	14.2	1.9	7.1	10.1
B1-SR	2.0	6.3	8.2	0.8	3.9	5.1
B1-450-SA	1.1	2.2	3.0	0.3	1.0	1.5
Case:	Exceedance area, 10% NPP loss			Exceedance area, 20% NPP loss		
stable land cover	2050	2075	2100	2050	2075	2100
A1-SR	4.8	13.5	17.0	2.7	8.9	12.5
B1-SR	2.7	7.6	9.6	1.2	4.7	6.2
B1-450-SA	1.7	3.0	3.9	0.6	1.5	1.9

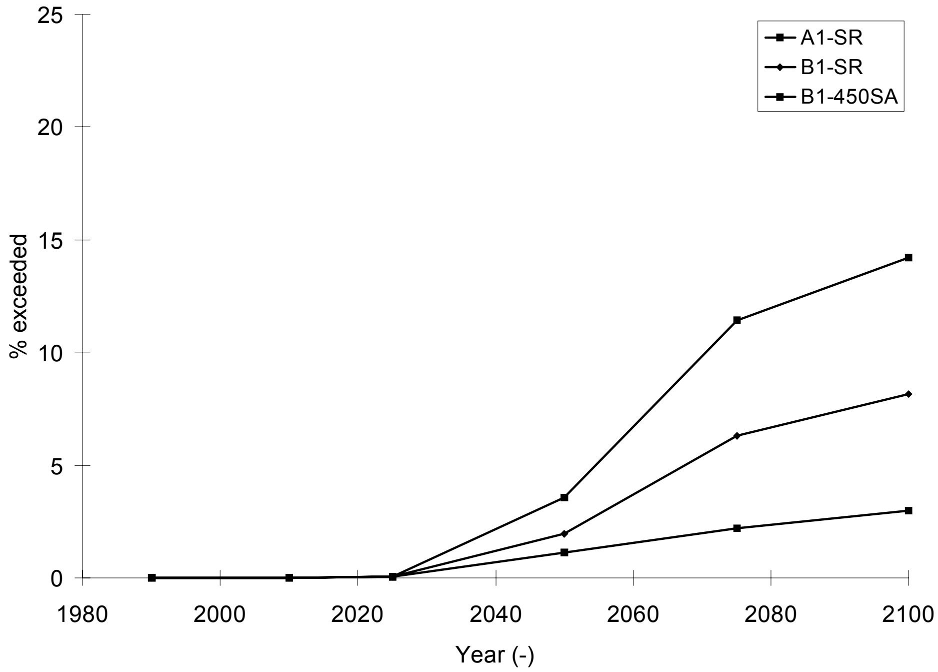

Figure 15 Temporal change of the area in which the acceptable effect of 10% becomes exceeded, allowing changes in vegetation (as % of total area under analysis)

3.3 Critical Climate and Its Exceedance

In this section we present the results of applying the critical climate approach to the A1-SR, B1-SR and B1-450-SA September scenarios. Details about the approach itself are given in Section 2.5. The aim of the application is to determine the spatial and temporal variation of climate exceedances, analogous to the evaluation of the exceedances of critical levels and loads (Section 3.4 and 3.5). We use the defined 10 and 20% NPP loss as acceptable climate change effects. The levels are validated by evaluating acceptable effects for other environmental issues and on the historic NPP variation (Section 2.5).

The A1-SR scenario result in the largest area in which the critical climate is exceeded. The smallest area is computed for the B1-450-SA scenario. Differences between the scenarios are increasing up to 2100. Until 2050 only minor exceedances are computed for all three scenarios, followed by an increase of the exceeded area up to 2100 (Table 4). For example, the

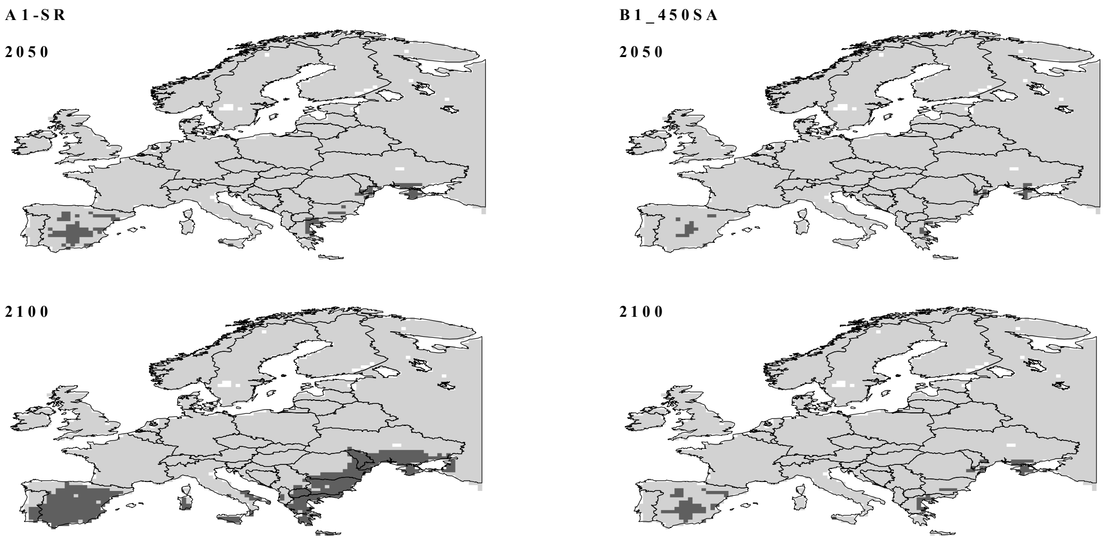

Figure 16 Exceedances (dark area) of the critical climate in 2050 and 2100 for the A1-SR (a) and B1-450-SA (b) scenario accepting a NPP loss of 10% and allowing vegetation changes

exceeded area is 14.2%, 8.2% and 3.0% in 2100 for the A1-SR, B1-SR and B1-450-SA scenario (see Figure 15). The highest increase between 2050 and 2100 is computed for the A1-SR scenario, due to largest changes in climate.

Mainly Southern and South-eastern Europe have areas where the critical climate is exceeded (Figure 16). We computed exceedances in this part of Europe, even for the mitigation scenario (i.e. B1-450-SA). The concentration of exceeded area in Southern Europe and South-Eastern Europe is the result of a combination of higher temperatures and lower precipitation. In certain grid cells the reduction of the precipitation in between 1990 and 2100 range from 200 (B1-450-SA) to 350 mm (A1-SR scenario). Higher temperatures lead to increased evapotranspiration rates, which in turn enhances the drought stress.

The extent of exceedances differs between the two adaptation cases and the two levels of acceptable effects (Table 4). Allowing no adaptation of the land-cover results in more exceedances compared to the case in which the ecosystems can change (compare Figure 17 with Figure 16a). In 2100 the difference for the A1-SR scenario was 3%. The additional areas are distributed over the whole of Europe. Higher temperatures in Northern Europe, for example, are unsuitable for current vegetation. Changing the acceptable effect for the critical climate threshold from 10 to 20% NPP loss, greatly reduces the area of exceedances.

To summarize the application of the critical climate approach for the September scenarios, up to 2050 only a few areas in Southern and South-eastern Europe will experience an exceedance. Allowing the land cover to adapt, the area increases until 2100 up to a maximum of 14% of European area. Decreasing precipitation rates in combination with increasing temperature causes this effect. Additional grids in the whole of Europe will become exceeded, if changes in land cover are not allowed. The additional exceedances are caused by the lower adaptation capacity of the current land cover. The sensitivity of vegetation in a particular area strongly depends on the current biome type and climate conditions (i.e. whether the current biome has a broad or narrow range of suitable climate conditions and whether the current climate conditions are close to the environmental limits).

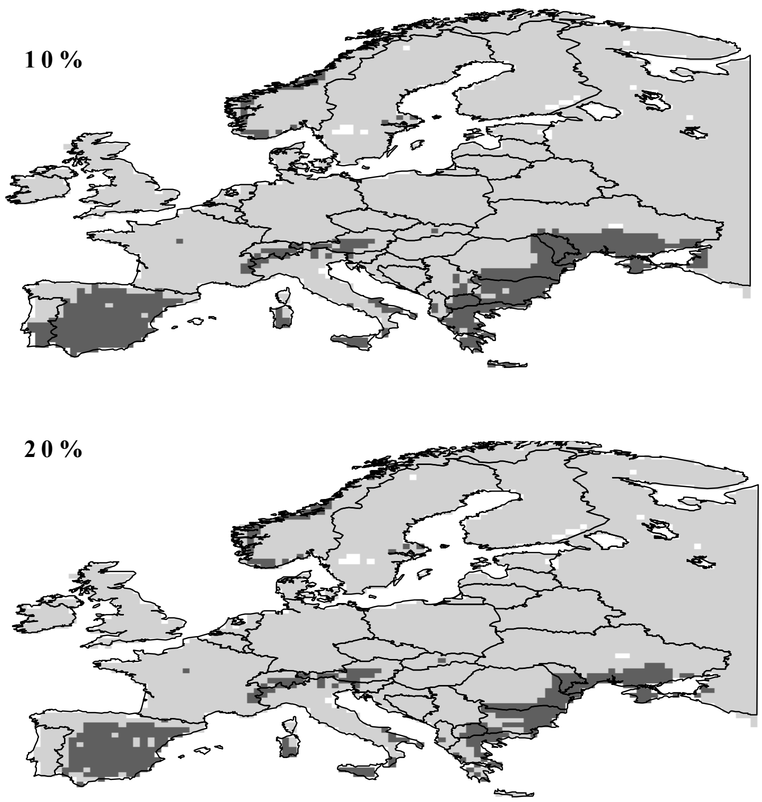

Figure 17 Area where critical climate threshold is exceeded for two different acceptable effects for the threshold: a 10 % loss in NPP (a), and a 20% loss in NPP (b), allowing no changes in vegetation

3.4 Critical Loads (Depositions) and Their Exceedances

Critical Loads

The data needed to calculate critical loads of acidity can be inferred from the calculation method (SMB model) described in Section 2.3. In particular, these are:

- Soil and forest data: The about 110,000 forest-soil combinations were obtained by overlaying the most recent FAO soil map with a preliminary version of the 1x1 km^2 PELCOM European land cover data base (http://www.geodan.nl/ec_lu/).
- Base cation and chloride deposition: obtained by interpolating observations from about 100 background measuring stations in the network of the EMEP Chemical Coordination Center (Hjellbrekke *et al.*, 1997) at each of the 0.5°x0.5° land-based grid cells covering Europe. To smooth inter-annual fluctuations data were averaged over the period 1991-95.
- Base cation weathering rates: derived from soil texture and parent material classes assigned to FAO soil types (Gregor *et al.*, 1996) (Appendix IV).
- Base cation and nitrogen uptake: computed from (latitude dependent) element contents of tree compartments and net forest growth, which in turn is estimated from site quality and climate region.
- Temperature, precipitation and sunshine data: monthly output of the IMAGE model under the 3 September scenarios (reference years 1990, 2010, 2025, 2050, 2075 and 2100) is used to compute evapotranspiration. Actual evapotranspiration is computed with the same

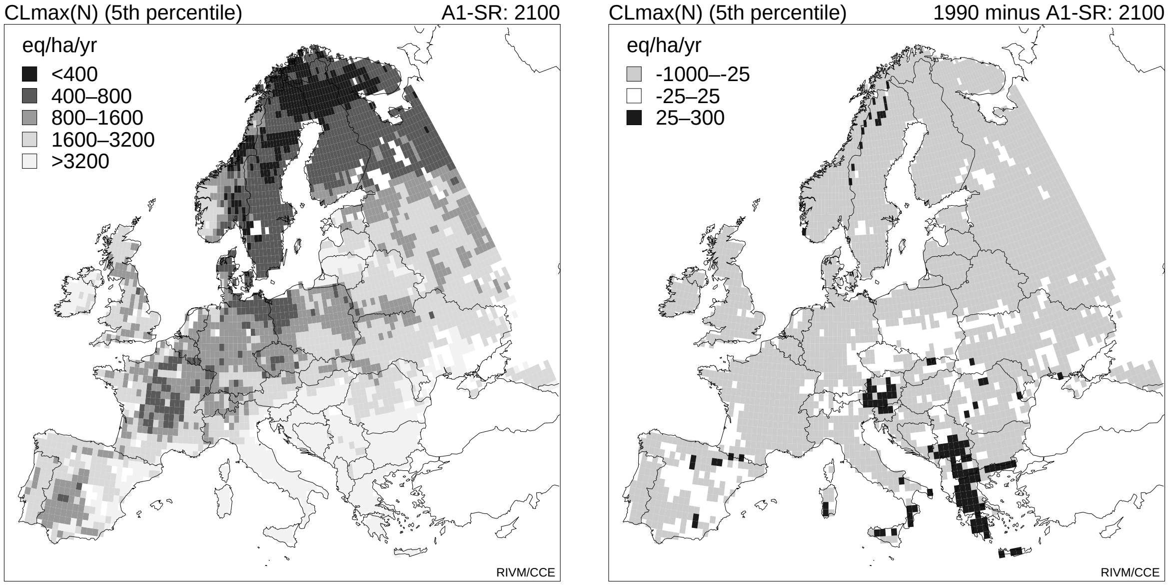

Figure 18 5-th percentile of the distribution of CL_{max}(N) in each 0.5°x0.5° grid cell in 2100 under the climate according to the A1-SR scenario (left) and the difference to the same quantity under present (1990) climate (right).

model as implemented in IMAGE (Prentice *et al.*, 1993), but with site-dependent water holding capacity.

The above input data have been used to compute the quantities CL_{max}(S), CL_{min}(N) and CL_{max}(S) which determine the critical load functions for acidity. From these data the cumulative distribution function of critical loads in each 0.5°x0.5° grid cell covering Europe is obtained, which allows the calculation of any desired statistic (see Section 2.3).

As an example, Figure 18 shows the 5-th percentile of CL_{max}(N) in every 0.5°x0.5° grid cell for the year 2100 under the scenario A1-SR and the difference to the same quantity under present (1990) climate. The left map shows that the most sensitive forest soils are located in Northern Europe. The map on the right that in most parts of Europe critical loads become higher under climate change; only on the Balkans and in parts of the Alps soils become more sensitive to acidifying deposition. The figure for CL_{max}(S) (not shown here) is similar in amount and pattern. The reason for this is that the variables are closely connected (see Section 2.3).

Exceedances

Critical loads have been developed as a sensitivity indicator for ecosystems which is directly comparable to depositions (of N and S). If the deposition is greater than the critical load, or the pair of depositions (N_{dep},S_{dep}) lies outside the critical load function (see Figure 3, Section 2.3), we say the critical loads are exceeded. While in the case of a single pollutant the exceedance is uniquely determined (Ex=Dep-CL), there is no unique exceedance (=amount of deposition to be reduced to reach non-exceedance) in the case of acidifying N and S. This is illustrated by the example in Figure 3: Let the point E denote the (current) deposition of N and S. Reducing N_{dep} substantially, one reaches the point Z1 and thus non-exceedance without reducing S_{dep}; on the other hand one can reach non-exceedance by only reducing S_{dep} (by a smaller amount) until reaching Z3; finally, with a smaller reduction of both N_{dep} and S_{dep} one can reach non-exceedance as well (e.g. point Z2). In practice external factors, such as the costs of emission reduction measures, will determine the path to be followed to reach zero

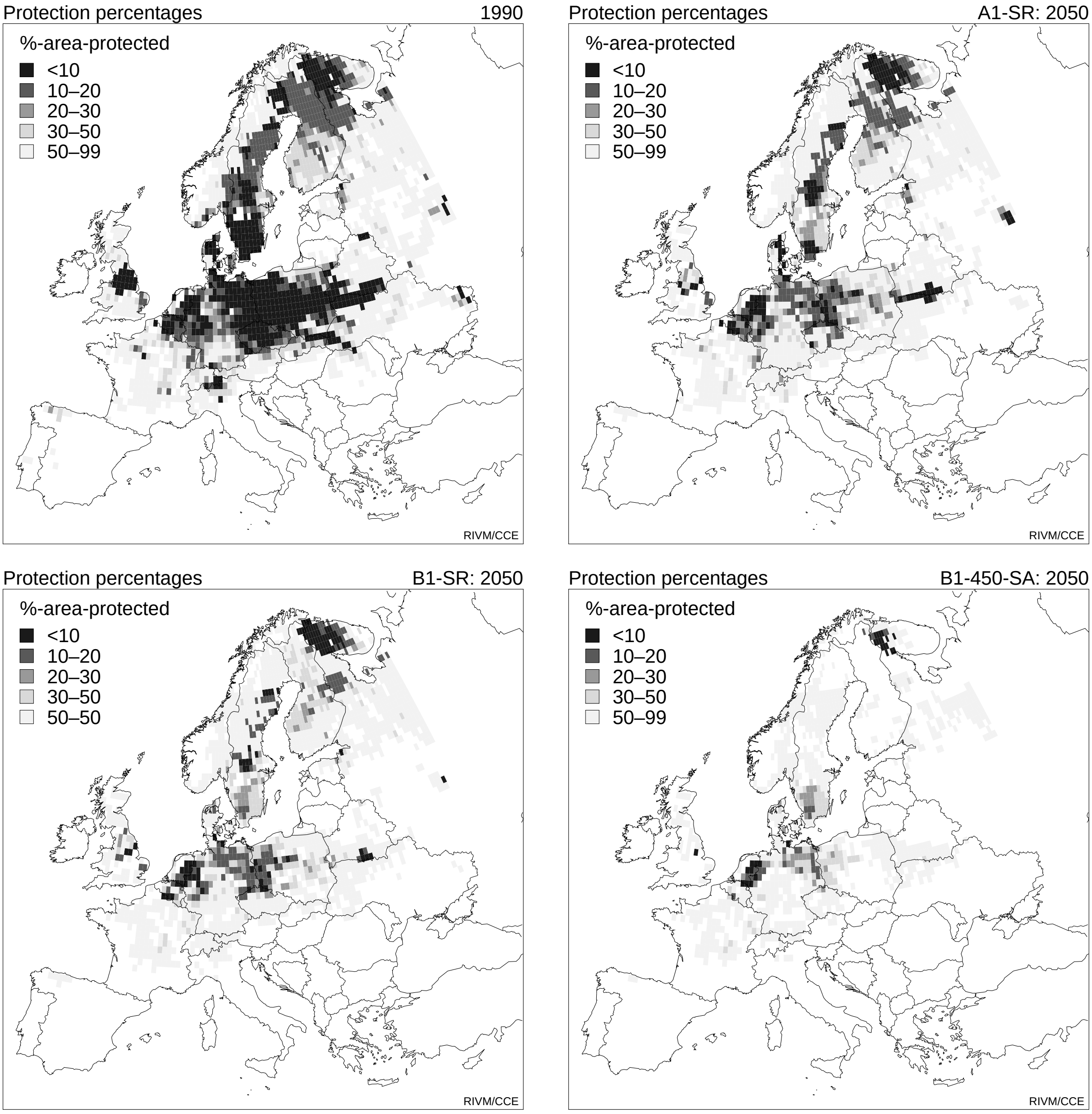

Figure 19 Ecosystem protection percentages, i.e. percentage of ecosystems in the grid cells with depositions are below critical loads, for the year 1990 and the year 2050 for the N and S deposition under the three September scenarios (white areas: protection = 100%).

exceedance. However, it is always possible to determine whether critical loads are exceeded or not, i.e. one can always compute the percentage of ecosystem area in a grid cell for which critical loads are not exceeded, called the ecosystem protection percentage.

In Figure 19 the ecosystem protection percentages in each 0.5°x0.5° grid cell are shown for the year 1990 and the year 2050 for the N and S deposition under the three September scenarios. Compared to 1990, the overall protection of ecosystems increases in the year 2050 for all three scenarios, i.e. the area with critical loads for acidity exceeded decreases. While for the A1-SR scenario, and to a lesser extent also for the B1-SR scenario, large areas of central Europe and Scandinavia are still exceeded, the B1-450-SA scenario shows high protection percentages for almost all of Europe, with the exception of the Netherlands, northern Germany and southern Scandinavia.

When computing exceedances under climate change scenarios, one has to consider that climate change influences critical loads directly (see Section 2.3) and that also the long-range transport and deposition of pollutants is influenced by climate change (see Section 2.2). However, the differences using climate-changed critical loads (CLs) and climate-change source-receptor matrices (SRMs) or present CLs and SRMs are small. For example, in 2050 under the A1-SR scenario the European area protected is 71.7% and 68.8%, respectively. But this finding has to be treated with caution and might have to be revised when truly climate-change SRMs become available (see Section 2.2.1).

As explained above, no unique exceedance exists in the case of acidity critical loads. Intuitively, the reduction required in S and N deposition to reach point Z2 in Figure 3 (Section 2.3), i.e. the "shortest" distance to the critical load function, seems a good measure for exceedance. Thus we define the exceedance for a given pair of depositions (N_{dep},S_{dep}) and a given critical load function as the sum of the N and S deposition reduction required to reach the critical load function by the "shortest" path, i.e. $Ex(N_{dep},S_{dep})=\Delta N+\Delta S$ (and Ex=0 for non-exceedance).

For an assessment, all critical load functions within a grid cell have to be considered simultaneously, and each ecosystem contributes with its area A_i, i=1,...,N (N=number of ecosystems in the grid cell). Let $Ex_i(N_{dep},S_{dep})$, i=1,..,N, be the exceedance function for ecosystem i as defined above, then we define the average accumulated exceedance (AAE) as:

$$AAE(N_{dep},S_{dep}) = \sum_{i=1}^{N} A_i \, Ex_i(N_{dep},S_{dep}) / \sum_{i=1}^{N} A_i$$

The average accumulated exceedance has the same dimension as deposition and thus they can be directly compared. In Figure B the AAE for the year 1990 and the year 2050 under the three September scenarios is displayed. While the protection percentage tells the extent (area) of critical load exceedances, the AAE gives an indication of the (grid-averaged) amount by which critical loads are exceeded. Comparison of Figure 19 and Figure 20 shows that there is a fairly high correlation between extent and amount of exceedance, but also shows the differences. While critical loads are exceeded in large areas of Scandinavia (Figure 19), the amount by which they are exceeded is relatively small (Figure 20). Only in the Dutch-German border area are critical loads widely and highly exceeded in 2050 even under the most stringent B1-450-SA scenario.

In the negotiations for the recently signed multi-pollutant, multi-effects protocol under the LRTAP Convention, the average accumulated exceedance has turned out to be a robust indicator of critical load exceedances in the integrated assessment work on cost-effective emission reduction scenarios. Therefore it shall also be used in the AIR-CLIM work for analyzing future climate change and air pollution scenarios.

Future Work

The basic framework for analyzing S and N deposition scenarios and their impacts on critical loads has been set up. Future work includes updating data bases, both with respect to critical loads and deposition scenarios as well as adding additional features for analyzing the impact of scenarios, e.g. country-specific comparisons of scenarios with respect to their air pollution impacts.

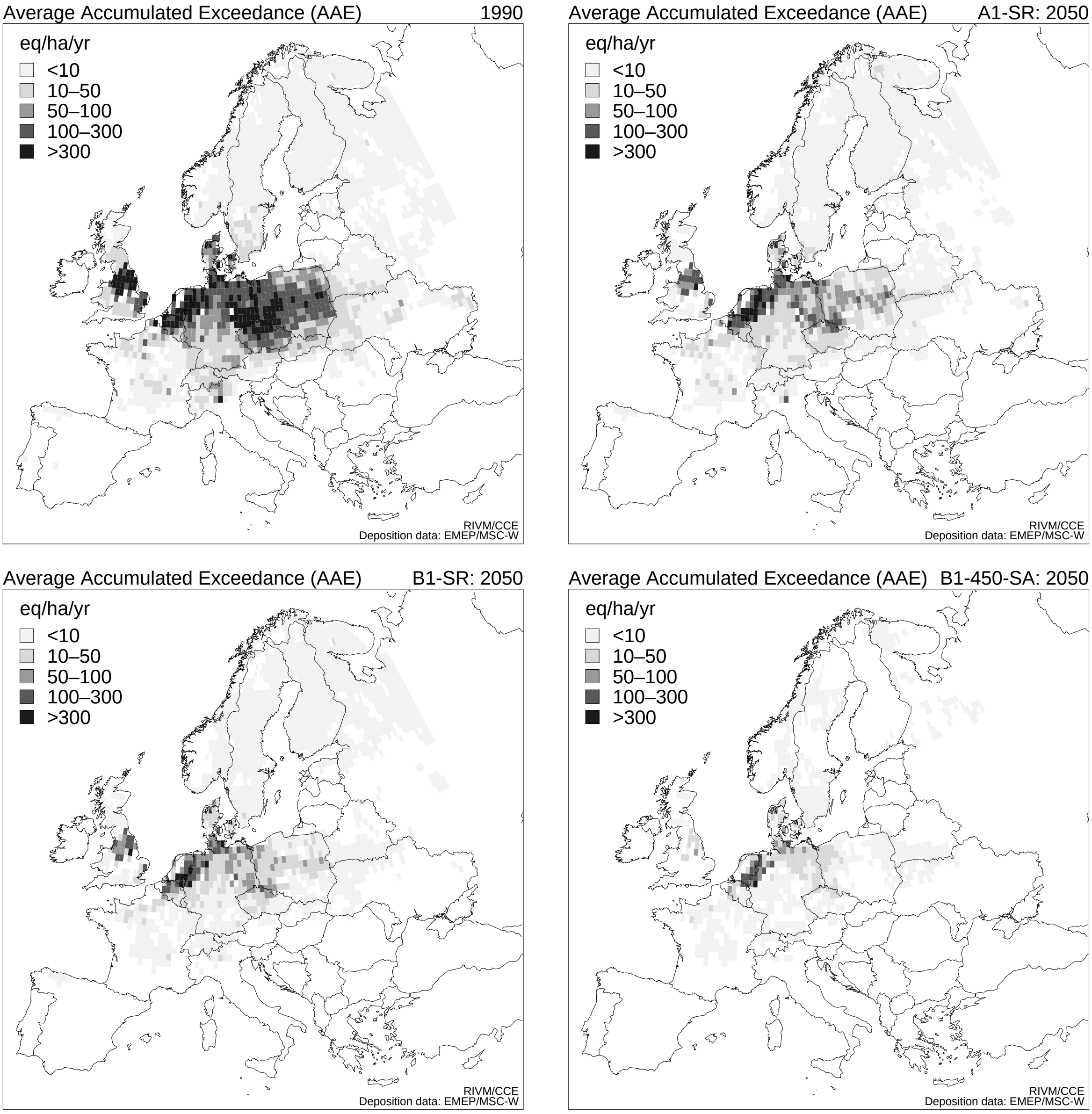

Figure 20 Average accumulated exceedances (AAE) for the year 1990 and the year 2050 for the N and S deposition under the three September scenarios (white areas: AAE=0).

3.5 Critical Levels (Concentrations)

Monthly critical concentrations for SO_2 (S), NO_x (N) and NH_3 (N) for each reference year and each scenario have been calculated using the estimated stomatal conductance and the reference flux calculated for that land cover in 1990 (see Section 2.4). In order to explore the impact of the climate scenarios we compare the critical concentration of SO_2 for A1-SR and B1-SR in 2100 with the critical level for 1990. Figure 21 shows the ratio of X_{crit}'(2100) to X_{crit}(1990) for SO_2 for the scenarios A1-SR and B1-SR. The results show that in both scenarios in much of the continent the change is less than 20%.

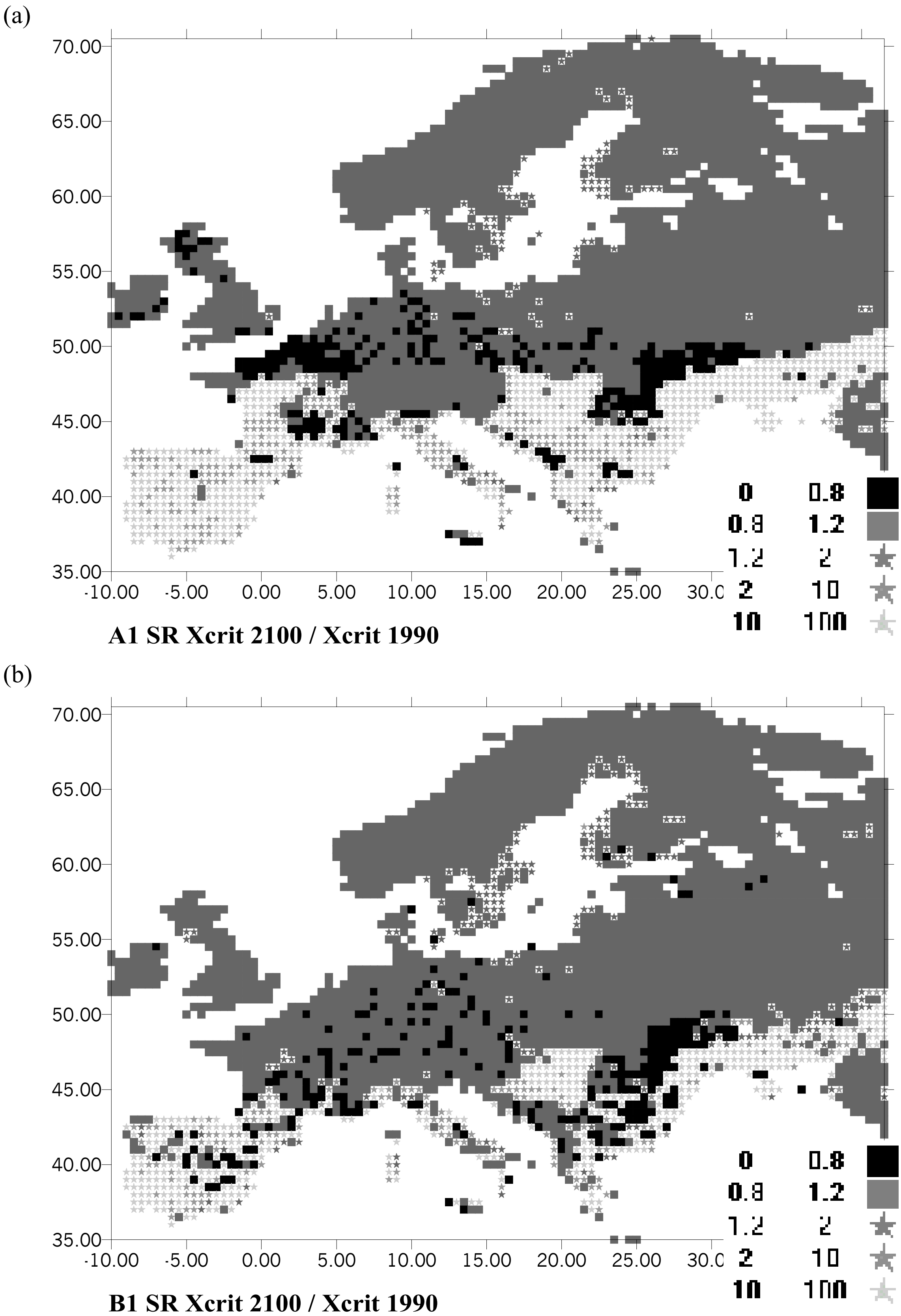

Figure 21 Ratio of X_{crit}'(2100) to X_{crit}(1990) for SO_2 for the scenarios (a) A1-SR and (b) B1-SR. Grey areas indicate differences of less than 20% are, black areas if the sensitivity increases by more than 20% of the 1990 critical limits. Stars indicate grid cells where the sensitivity in 2100 is lower than in 1990, thereby the shading indicates the degree of the decrease.

The largest impact is around the Mediterranean where in some areas the vegetation becomes more sensitive and would require concentrations at least 20% lower than in 1990 to be protected. Other areas in Southern Europe become slightly or much less sensitive and the concentrations could apparently be larger there without exceeding the reference flux. An area around the Baltic also appears to become less sensitive. A comparison of the scenarios shows that, the area where critical concentrations change more than 20% is larger for A1-SR than for B1-SR, predictably as the climate change is larger.

3.6 Reduction Costs

The pilot version of the submodule for add-on emission reduction options has been tested for SO_2 emission reduction in three regions, viz. OECD Europe, Eastern Europe and Former USSR. The data on emission reduction options have been extracted from the RAINS database. The options range from Flue Gas Desulphurisation to the use of low sulphur fuels. Also, emission factors of the RAINS database have been used, since RAINS has a more detailed fuel categorisation, especially relevant for SO_2 and NO_x; IMAGE fuel categories are at the moment more focused on carbon intensity. National data have been aggregated in order to derive regional averages.

The resulting emission factors for regions and IMAGE fuel categories have to be compared with those of IMAGE within the next months. Furthermore, application of options to only a part of the fuel consumption due to higher aggregation level of fuels or / and technology categories in IMAGE (viz. diesel versus light liquid) has to be analysed and taken into account in the next period. Also, RAINS data on present policies have to be included in the submodule. At this moment, a baseline without any policies has been calculated.

Developments over time of average installed capacity and full load hours (relevant for the specific investment costs) has assumed to be constant (1990 values) since no scenario consistent assumptions were made yet.

These shortcomings have to be taken into account when looking at the preliminary results.

The emissions for the Former USSR include also the non-European regions. This makes it for the moment impossible to compare with objectives of the Second Sulphur Protocol.

Figure 22 presents the marginal emission reduction costs for the year 2050 according to the A1 baseline scenario (no policies) as a function of the regional SO_2 emission reduction %. In this graph, the marginal costs can be compared easily for different regions. In general, the marginal emission reduction costs in the Former USSR are relatively low and in OECD Europe relatively high, although the differences are small in some ranges of emission reduction. In all three regions, the majority of emissions (60% to 68%) stems from coal. Oil accounts for almost the rest of the emissions. In OECD Europe, the sulphur content of oil is on average significantly lower (due to policies) than in the other regions, resulting in higher marginal costs. The average installed capacity size is in Former USSR assumed to be larger (like in 1990) which results in lower marginal costs. One has to bear in mind that efficiency improvements and fuel switch are not expressed in this marginal costs curve, since reduction rates are expressed relative to the baseline.

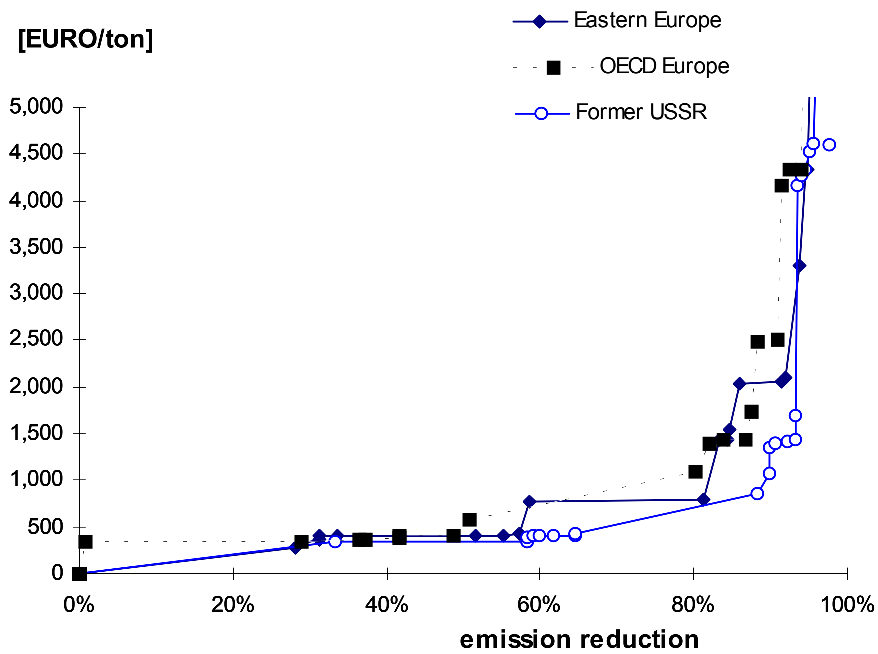

Figure 22 Marginal SO_2 reduction costs curves for three regions in the year 2050 according to the baseline scenario A1: no policies

Figure 23 presents for the year 2050 the marginal costs (right vertical axe) and the total cumulative costs (left vertical axe) as a function of the absolute SO_2 emission reduction in the region, starting from the A1 baseline without policy. For each region, a separate graph is drawn. Obviously, the feasible SO_2 emission reduction in 2050 starting from the A1 baseline without policies is the largest in the Former USSR since the emissions are the largest in this region (35000 kton). The emissions in OECD Europe are 24000 kton and for Eastern Europe 11000 kton. The baseline growth of SO_2 emissions relative to the year 1990 is around 15% for all regions, which can be considered as moderate. This is due to efficiency improvements and fuel switch towards natural gas and biomass which take place autonomously in the energy system.

The total costs of emission reduction can be put in perspective by comparison with the Gross Regional Product (GRP). For OECD Europe, the costs to achieve 80% emission reduction with respect to the baseline would take around 0.12% of the 2050 GRP. The costs for Eastern Europe to achieve a similar reduction share would account for 0.36% and for the Former USSR for 0.5% of GRP.

According to the Second Sulphur Protocol, OECD Europe has a target for SO_2 emissions lower than 8000 kton, requiring an emission reduction of approximately 16000 kton or almost 70% of the baseline emissions. Eastern Europe has a target of almost 7000 kton. The required emission reduction is 4000 kton or 40% of the baseline emissions. This would account in both regions for approximately 0.75% of GRP.

Although the results are draft and incomplete, it is shown that the submodule for add-on emission reduction options can generate reasonable results. Assumptions and other input data have to be refined and completed and the database has to be completed for other regions and NO_x emission reduction options.

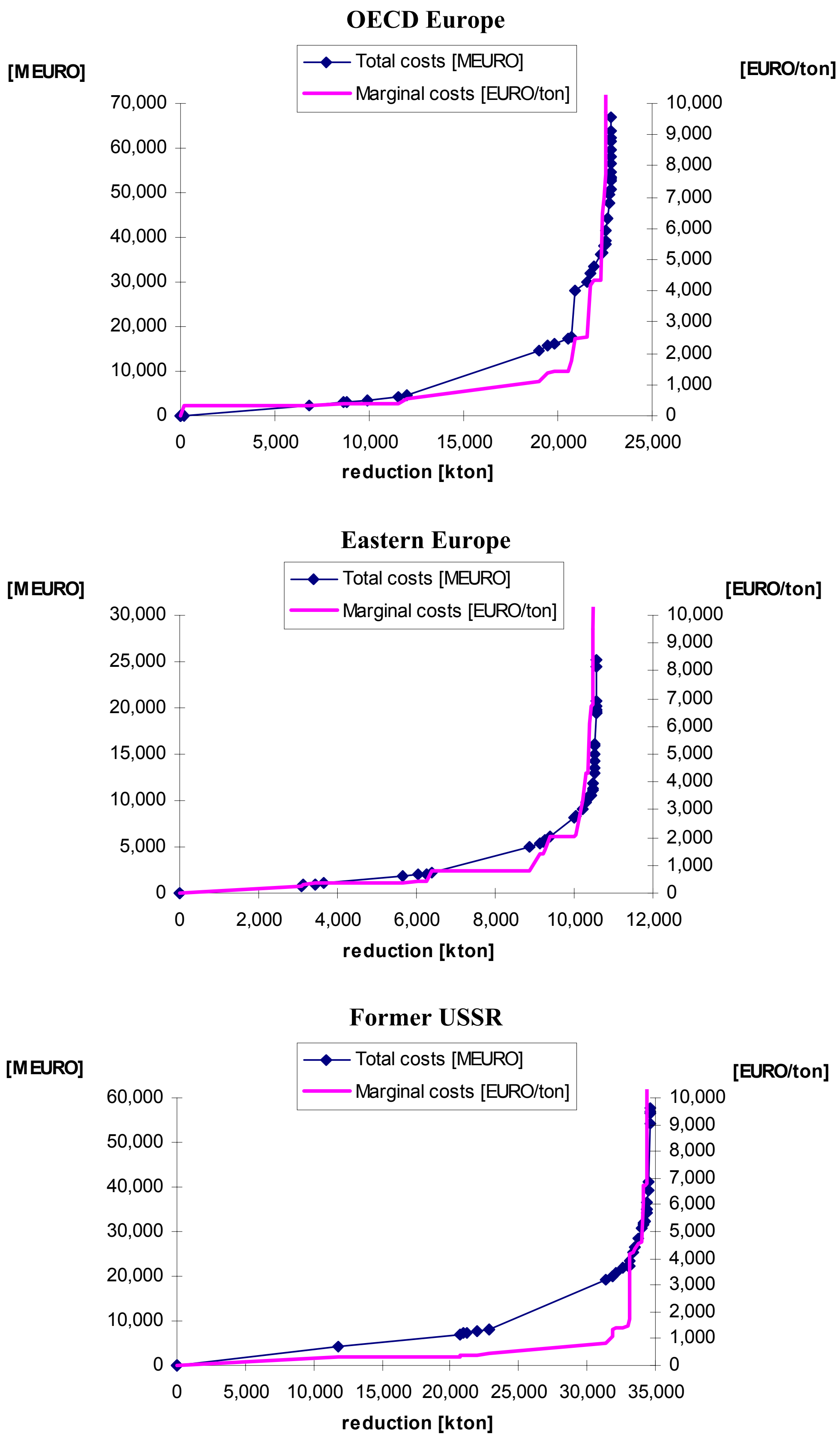

Figure 23 Marginal and total SO_2 reduction costs for three regions in the year 2050 according to the baseline scenario A1: no policies

3.7 Sensitivity of Climate Change to SO_2 Emissions

The SO_2 emissions have a cooling effect on the climate and in this project we assess the importance of this effect in Europe. For that purpose two experiments have been carried out. The highest greenhouse gas emissions of the September scenarios have been combined with the lowest SO_2 emissions (Experiment 1) and vice versa (Experiment 2) (see Table 5 for definition of the experiments). For these experiments the climate change and the exceedance of the critical climate in Europe have been quantified.

Interestingly, the globally averaged temperature is not affected by reducing or increasing the SO_2 emissions, i.e. the development for A1-SR and Experiment 1 and for B1-450-SA and Experiment 2 are identical. However, the picture changes if climate change is analyzed in a regionally disaggregated way.

This might be seen as a contradiction to the results of (Posch *et al.*, 1996). They had analyzed the difference between a high SO_2 and a low SO_2 scenario. Thereby they calculated among others a difference in the global temperature in 2100 of 0.5°C. The difference between their two scenarios for global SO_2 emissions was 101 Tg S in 2050 and 132 Tg S in 2100. The differences between A1-SR and B1-450-SA, however, are only 84 Tg S in 2050 and 43 Tg S in 2100. That means while in the analysis of Posch *et al.* the SO_2 difference monotonously increases in parallel to the increasing climate change, in our analysis the difference reaches a peak around 2040. Comparisons between the temperature changes in Europe calculated in our analysis with the zonally averaged temperature change calculated by Posch *et al.* show that the results of the two analyses are consistent.

Applying the A1-SR greenhouse gas scenario in combination with a low sulfur scenario (Experiment 1) results in significant more grid cells for which the critical climate values are exceeded than in the A1-SR scenario (Table 5). The largest differences between the two scenarios occur between 2010 and 2050, due to relatively high sulfur concentrations in A1-SR and the starting climate effect of greenhouse gases. After 2050, the global sulfur emissions decrease significantly for all scenarios, reaching 1990 levels for A1-SR and falling far below for B1-450-SA. This is the reason the differences between A1-SR and Experiment 1 become smaller, despite increasing climate change. As net effect the critical climate will become exceeded in about the same areas (mainly Southern and South-eastern Europe) for Experiment 1 as for A1-SR, 10-15 years earlier, however.

Combining the B1-SA-450 greenhouse gas scenario with a high sulfur emission scenario (Experiment 2) leads to a stronger cooling effect, resulting in less extreme changes in climate.

Table 5 Definition of experiments in terms of global emissions and calculated exceedance areas for 2050, 2075 and 2100 for the case of unlimited migration and for an acceptable NPP loss of 10%

	Experiment definition		Exceedance areas		
	GHG	SO_2	2050	2075	2100
A1-SR			3.6	11.4	14.2
Experiment 1	as A1-SR	as B1-450-SA	7.6	12.9	14.9
B1-450-SA			1.1	2.2	3.0
Experiment 2	as B1-450-SA	as A1-SR	0.0	0.8	1.7

This leads to a delay of the first occurrence of exceedance (after 2050) and to less grid cells that will experience exceedance at all.

3.8 Main Findings

The analysis carried out so far within AIR-CLIM is still preliminary as the methodology has still to be refined at some points. Some components (as the climate-change SRMs and the cost module) are to be added and the emission scenarios to be finalized. However, some preliminary scientific conclusions can be derived from the analysis of the September scenarios:

- *Emission trends*:
  - CO_2 emissions are expected to peak around 2040 to 2060 and then to decline.
  - The emissions of SO_2 and NO_x in Europe are expected to decline to the levels set in the LRTAP Protocols in the next years and afterwards to stabilize or slowly to decline further.
  - The global SO_2 emissions will peak around 2030 to 2040 and then decline. Assuming that countries without international agreements on SO_2 emissions will react similarly as Europe and Northern Europe to high SO_2 levels the decline will be steep and the global SO_2 emissions in 2100 about the same level as in 1990 or lower.

- *Costs of SO_2 emission reduction*:
  For OECD Europe, the costs to achieve 80% reduction of the 2050 SO_2 emissions would take around 0.1% of the 2050 Gross Regional Product (GRP) for the A1-SR scenario, i.e. the scenario with the highest SO_2 emissions under analysis here. The costs for Eastern Europe to achieve a similar reduction share would account for 0.4% and for the Former USSR for 0.5% of GRP.

- *Impact of SO_2 on climate change*:
  Contrary to earlier studies, only a small effect of SO_2 emissions on climate change *in 2100* is calculated. The reason for this is the decrease of the (global) SO_2 emissions to 1990 levels or lower while former studies assumed a continuing increase. Higher SO_2 emissions delay (but do not avoid) the exceedance of critical climate values in Europe.

- *Impact of climate change on regional air pollution*:
  As climate-change SRMs are not yet available, the climate analogy approach has been used to calculate regional air pollution under climate change. Using this approach the impact is small. However, the analogy approach is very crude as e.g. changes in wind pattern are not taken into account. It is expected that SRMs derived from results of the EMEP model calculated with GCM output will be better. Only with these new SRMs the question how much regional air pollution is affected by climate change can really be answered.

- *Impact of climate change on critical deposition (loads) and its exceedances*:
  - Under climate change the critical loads increase, i.e. the ecosystems become less sensitive with time, with the exception of Southern Europe.
  - However, even under the lowest deposition scenario, the critical loads are still exceeded in some areas (Germany, UK, East Europe) in 2100.

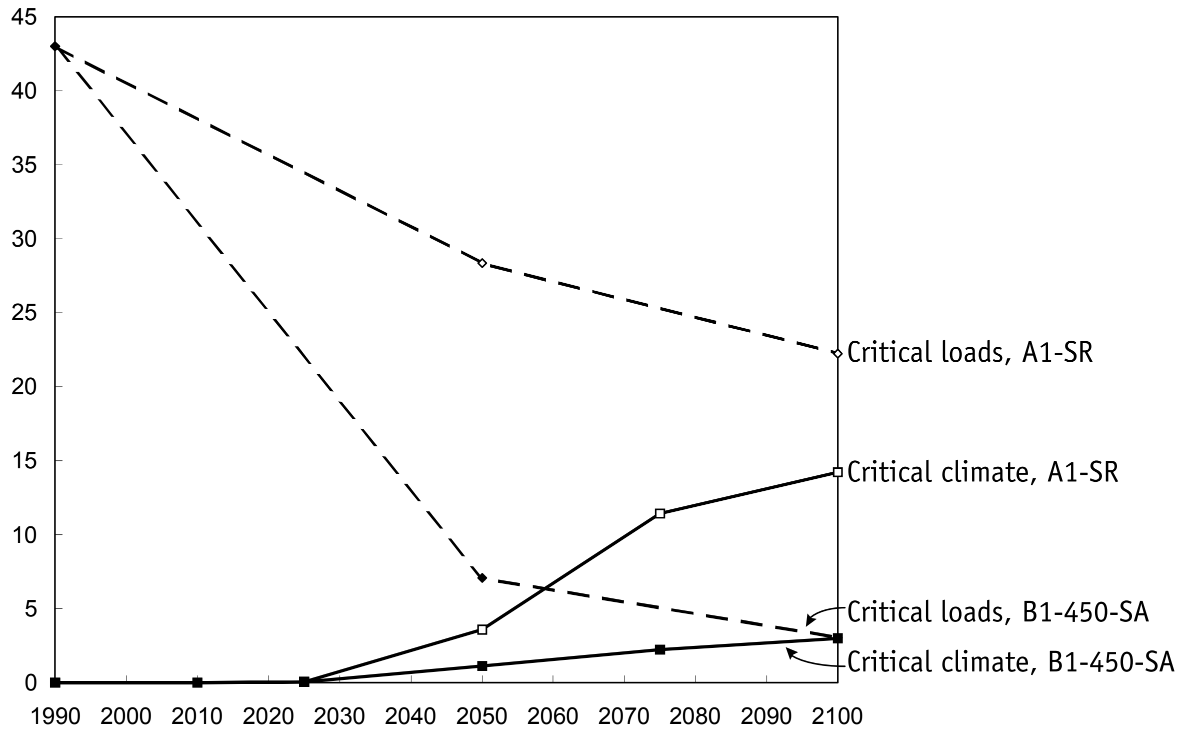

Figure 24 Exceedance areas [%] for the critical thresholds for the scenarios A1-SR and B1-450-SA (critical climate in % of natural ecosystems for 10% NPP as acceptable effect allowing vegetation changes; critical load in % of forest ecosystems assuming no vegetation changes)

- *Impact of climate change on critical concentration (levels)*:
  - Critical levels increase in Central and Southern Europe under climate change. The reason for this is that in these areas the temperatures increase *and* precipitation decreases. Therefore, the stomata of the plants are more often closed and the uptake of pollutants by plants is reduced, the ecosystems become less sensitive.
  - Critical levels decrease in Northern Europe. In that area temperature also increases but there is sufficient precipitation so that the stomata are not less often closed as nowadays.
  - The increase of critical levels is much more marked for the A1-SR scenario than for the B1-SR and the B1-450-SA scenarios.

- *Critical climate and its exceedances*:
  - For current precipitation levels only severe temperature increases will lead to an exceedance of the acceptable effect of 10% net primary production (NPP) loss. Only in some areas in Southern Europe lower critical temperature changes are found. If current precipitation levels are reduced by 40%, in some areas temperature has even to *decrease* to avoid net primary production losses of more than 10%.
  - Three different types of responses can be distinguished: (1) Large parts of Northern Europe are only slightly sensitive to decreased precipitation levels, even if the temperature increases. (2) Middle Europe becomes less sensitive to reduced precipitation if the temperature increases. This is because higher temperatures stimulate NPP. (3) Southern Europe becomes even more sensitive to precipitation reductions for higher temperature.

    - Up to 2050 critical climate values will be exceeded only in a few areas in Southern and South-eastern Europe. The exceedance area increases up to a maximum of 14% of European area until 2100. Decreasing precipitation rates in combination with increasing temperature is responsible for this.
    - The A1-SR scenario results in the largest area in which the critical climate is exceeded. The smallest area is computed for the B1-450-SA scenario.

- *Development of areas for which the various critical thresholds are exceeded*:
  While the area for which critical climate is exceeded will increase with time, the exceedance area for acid deposition will decrease (see Figure 24). Thereby even in 2100 the exceedance areas for critical loads are still larger than those for critical climate.

In summary, it can tentatively be stated that climate change will make European vegetation in most regions less sensitive to acid deposition. Taking into account the emission trends the impacts of regional air pollution will decrease while the impacts of climate change increase. Different problems will be important in different regions: regional air pollution in Central and Northern Europe, and climate change in Southern Europe.

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APPENDIX

Appendix 1: Acronyms

AGCM	Atmospheric General Circulation Model
CGCM	Coupled (Atmosphere-Ocean) General Circulation Model
COP	Conference of the Parties
DKRZ	Deutsches Klimarechenzentrum (German Climate Research Center), Hamburg
EMEP	Co-operative Programme for Monitoring and Evaluation of the Long Range Transmission of Air Pollutants in Europe
EU	European Union
GCM	General Circulation Model
GDP	Gross Domestic Product
IIASA	International Institute for Applied Systems Analysis
IMAGE	Integrated Model to Assess the Greenhouse Effect
IPCC	Intergovernmental Panel on Climate Change
LADM	Lagrangian Acid Deposition Model
LRTAP	Convention on Long-Range Transboundary Air Pollution
MPI	Max Planck Institute
NPP	Net primary production
RAINS	Regional Acidification Information and Simulation
SIDDACLICH	Simulation, Diagnosis and Detection of the Anthropogenic Climate Change Project
SRM	Source-Receptor-Matrix
UNFCCC	U.N. Framework Convention on Climate Change
USSR	Union of Soviet Socialist Republics

Appendix 2: Mathematical description cost calculation in emissions module

All formulas for base and sight years; country / region specific data are underlined.

$$\text{Emission}_{c,s,f,k} = \sum_{c}\sum_{s}\sum_{k} \text{Activity}_{c,s,f} * \text{EF}_{c,s,f} * \text{ApplicationFactor}_{c,s,f,k} * (1 - \text{RemovalEfficiency}_{k})$$

<u>Activity</u> *[PJi]*
<u>ApplicationFactor</u> *[market share]*

$$\text{EF}_{c,s,f} = \frac{\text{MolSO}_2}{\text{MolS}} * \frac{\text{Scontent}_{c,s,f}}{\text{HeatingValue}_{c,s,f}} * (1 - \text{SulphurRetentionAsh}_{c,s,f})$$

EF *[ton/PJi]*
<u>Scontent</u> *[weight %]*
<u>Heating value</u> *[GJ/ton]*

$$\text{Investment}_{c,s,f,k} = a_k * \text{AverageCapacity}_{c,s,f,k}{}^{-b_k} * \text{RelativeFlueGasVolume}_f * (1 + \text{RetrofitFactor}_{c,k})$$

Investment *[EURO/kWth]*
<u>AverageCapacity</u> *[kWth]*

$$\text{O\&Mfixed}_{c,s,f,k} = \text{Investment}_{c,s,f,k} * \text{Fixedfraction}_{c,k}$$

O&Mfixed *[EURO/kWth]*
<u>Fixedfraction</u> *[fraction]*

$$\begin{aligned}\text{O\&Mvariable}_{c,s,f,k} = {} & \frac{\text{LabourDemand}_k * \text{LabourCost}_c}{3.6*10^{-3} * \text{LoadHours}_{c,s,f,k}} \\ & + \text{AdditionalElectricityDemand}_k * 10^6 * \text{ElectricityPrice}_{c,s} \\ & + \text{EF}_{c,s,f} * \text{RemovalEfficiency}_k \\ & * (\text{SorbentDemand}_k * \text{SorbentCosts}_c + \text{DisposalDemand}_k * \text{DisposalCosts}_c)\end{aligned}$$

O&Mvariable *[EURO/PJi]*
LabourDemand *[annual man years/GWth]*
<u>LabourCost</u> *[EURO/man year]*
AdditionalElectricityDemand *[GWh/PJi]*
ElectricityPrice *[EURO/kWh]*
SorbentDemand and DisposalDemand *[ton/ton SO_2]*
<u>SorbentCosts and DisposalCosts</u> *[EURO/ton]*

$$\text{AnnualInvestment}_{c,s,f,k} = \text{Investment}_{c,s,f,k} * \frac{(1 + \text{RealInterest}_c)^{\text{lifetime}_k} * \text{RealInterest}_c}{(1 + \text{RealInterest}_c)^{\text{lifetime}_k} - 1}$$

<u>RealInterest</u> *[%]*

$$\mathrm{CostsPJinput}_{c,s,f,k} = \frac{\mathrm{AnnualInvestment}_{c,s,f,k} + \mathrm{O\&Mfixed}_{c,s,f,k}}{3.6*10^{-9} * \mathrm{LoadHours}_{c,s,f,k}} + \mathrm{O\&Mvariable}_{c,s,f,k}$$

CostsPJinput *[EURO/PJi]*

$$\mathrm{CostsTonReduction}_{c,s,f,k} = \frac{\mathrm{CostsPJinput}_{c,s,f,k}}{\mathrm{EF}_{c,s,f} * \mathrm{RemovalEfficiency}_{k}}$$

CostsTonReduction *[EURO/ton avoided SO_2]*