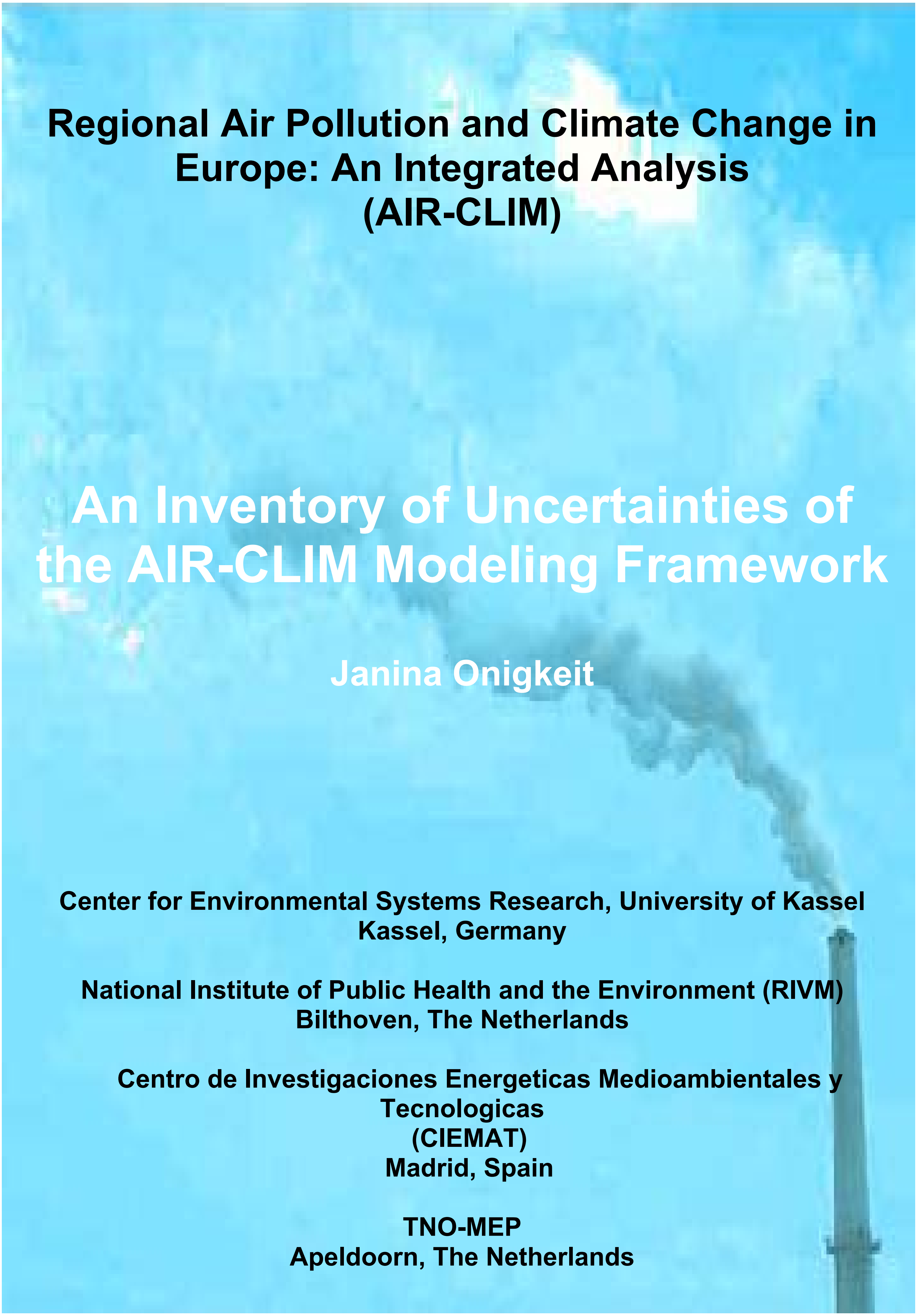

Regional Air Pollution and Climate Change in Europe: An Integrated Analysis (AIR-CLIM)

An Inventory of Uncertainties of the AIR-CLIM Modeling Framework

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Technical Report

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Report No. A0103

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1. Introduction

The AIR-CLIM project aims to analyze the coupled effects of regional air pollution and climate change in Europe. This includes the quantification of the impacts of these phenomena on natural ecosystems and the estimation of costs for the mitigation of both impacts by emission control measures. In order to do this, we used the modeling framework of component models as described in Alcamo et al. (2001) (see Figure 1). An inescapable characteristic of models and their results is that they are inexact approximations of reality. Hence, a key question in the AIR-CLIM project and other model-based studies is, what is the extent of this uncertainty? This information about uncertainty is especially needed when the results of such a modeling exercise are aimed to provide information for environmental decision making.

To estimate the uncertainty of the results of the AIR-CLIM modeling framework a five-step uncertainty analysis as outlined in Alcamo and Bartnicki (1987), can be used:

1. *Problem formulation,* in which the time and spatial scale of the problem are established.
2. *Inventory of uncertainties,* to collect the main sources of errors in a systematic way.
3. *Screening and ranking of uncertainties,* to set priorities for a quantitative evaluation.
4. *Quantitative evaluation of uncertainties,* in which a variety of analytical techniques is used.
5. *Application to routine calculations,* in which information about model uncertainty is used to supplement routine calculations.

Within this project, however, we focus on Step 1 and 2 and make, if possible, some preliminary estimates about Step 3. Step 4 and 5, however, are not covered within the AIR-CLIM project since they require a major research effort, which is outside the scope of the project. In the following sections we present a detailed and systematic inventory of uncertainties of the AIR-CLIM modeling framework.

1.1 Problem formulation

The magnitude of uncertainty of the modeling results depends on the variable and the time and spatial scale of interest. Before performing the uncertainty analysis it is therefore necessary to select and describe the output variables the uncertainty factors refer to. For the AIR-CLIM study these are

1. the extension of area (in km^2) where the critical load, the critical level or the critical climate will be exceeded in Europe;
2. where in Europe this will happen; and
3. the costs of mitigating CO_2 emissions as well as SO_2 and NO_x emissions to diminish the impacts described under points (1) and (2);

These results were calculated on a yearly averaged basis for the period 1990 to 2100. Before obtaining the results, however, a number of different model runs must be performed to obtain the variables for the aim of the AIR-CLIM project, namely the combined analysis of climate change and air pollution impacts. All these models and their contribution to the uncertainty of the overall results must be considered. Before presenting the details of the uncertainty analysis we therefore briefly describe the main steps of model calculations which also determines the structure of the uncertainty analysis.

1.2 Categories of uncertainty

The uncertainty of the AIR-CLIM results originate from very different factors of the modeling process such as parameter uncertainty but also uncertain knowledge of the processes included in the model. These types of uncertainty must be treated differently if the uncertainty of the results is to be quantified in a later step. Although this quantification is not done for this project, it is nevertheless helpful for the structure of the analysis to distinguish between the following aspects of model uncertainties:

Model structure, uncertainties resulting from the specified terms of the model especially the assumptions and processes taken or not taken into account in the model.
Parameters, uncertainties coming from the coefficients which are set constant in time and/or space.
Forcing functions, uncertainties from coefficients which inherently change in time and space.
Initial state, uncertainties related to boundary and initial conditions.
Model operation, resulting from the solution techniques of model equations and pre- and post-processing of model information.

It is important to note that there is a hierarchy within these aspects of uncertainty since e.g. parameters and forcing functions depend on the model structure. The model operation was evaluated for each sub model but is not always taken up in the following analysis since the used models deal with very complex issues but are not complicated in a mathematical sense.

1.3 Overview of uncertainty factors

The AIR-CLIM analysis is based on two scenarios described in the recently published Special Report on Emission Scenarios (Nakicenovic et al., 2000) of the Intergovernmental Panel on Climate Change (IPCC). From these two scenarios, namely the A1 and the B1 “world” we used population dynamics and economic growth within Europe and for the whole world as key driving forces of the modeling framework. We assume that these input variables have no uncertainty in the sense that analyzing these two scenarios already reflects the uncertainty or a range of possible futures.
The uncertainty analysis takes up the structure of the modeling framework by distinguishing a sequence of modeling steps:

1. *Modeling of emissions*
   a) Energy demand
   b) Secondary energy use (electricity, fuels)
   c) Primary energy use and production
   d) Greenhouse gas emissions (CO_2, CH_4, N_2O)

    e) Emissions of air pollutants (SO_2, NO_x, NH_3)

2. *Modeling climate change in Europe*

3. *Modeling the dispersion and chemical transformation of air pollutants*
    a) Standard source receptor matrices (SRMs)
    b) Climate changed SRMs

4. *Modeling impacts on natural ecosystems*
    a) Critical loads under climate change conditions
    b) Exceedance areas for critical loads
    c) Critical levels under climate change conditions
    d) Exceedance areas for critical levels
    e) Critical climate
    f) Exceedance areas for critical climate

5. *Modeling the costs for emission mitigation*
    a) Mitigation costs for greenhouse gas emissions
    b) Mitigation costs for SO_2 and NO_x emissions

Since the models of this framework reflect very complex issues in a spatially explicit way they require a lot of parameters and/or a large amount of input data, which are all more or less uncertain. For this analysis, however, we list only those parameters and assumptions that, according to the experts view, contribute most to the uncertainty of the AIR-CLIM results.

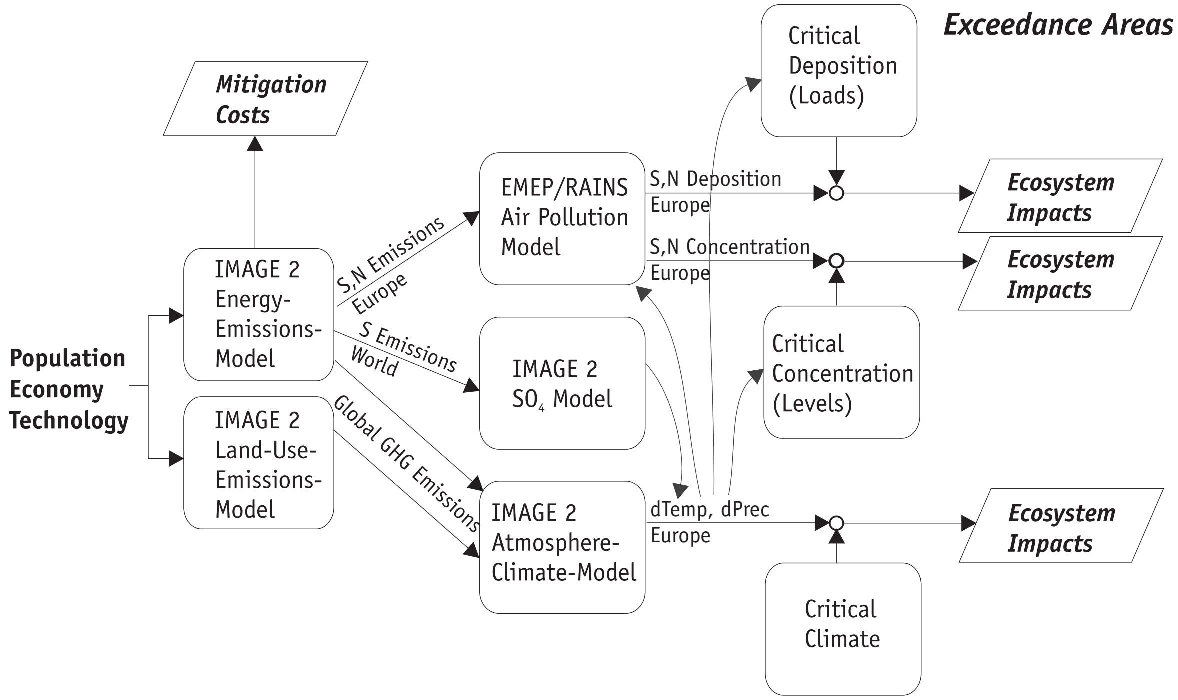

Figure 1 The AIR-CLIM modeling framework.

2. Modeling of emissions

As a prerequisite for the impact assessment of the AIR-CLIM project we need emission pathways for greenhouse gases and air pollutants. We focus on the greenhouse gases carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) and on the emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and ammonia (NH_3) to cover the air pollution aspect of the analysis. Three of these gases, namely CO_2 emissions as the major cause for the greenhouse effect and SO_2 and NO_x emissions as the major causes for soil acidification mainly originate from the process of energy production. The focus of the emission part of the uncertainty analysis will therefore be on energy production.

Greenhouse gas emissions were basically derived from population and economic growth of the two IPCC scenarios A1B (=A1 Balanced) and B1. For further information about the assumptions and storylines underlying these scenarios see (Nakicenovic et al., 2000).

To translate the information about population and economic development into greenhouse gas and air pollutant emissions the Targets IMage Energy Regional model (TIMER) was used (see e.g. de Vries et al., 1999). Here, we give a rough outline of the way emissions were calculated. We will go more into detail when we specify the uncertainty factors under the different processes that contribute to the overall uncertainty of emission calculations.

In a preparatory step, the population and economic data given for the four IPCC regions must be transferred to the 17 regions of the TIMER model. Then, the energy demand for each of these regions is calculated. The next processes contributing significantly to the uncertainty of the model output are the modeling of electricity generation followed by the calculation of primary energy use. From the seven different categories of energy carriers for primary energy production we finally obtain emissions of CO_2 and other greenhouse gases.

For the mitigation scenarios a carbon tax is introduced which accelerates energy efficiency improvements and a shift to non-fossil energy carriers. For more details about the greenhouse gas mitigation scenarios and their costs see Mayerhofer et al. (2001) and section 6 of this report.

Air pollutant emissions from the energy sector are calculated by multiplying yearly energy production with a sector- and fuel specific emission factor. For the emission mitigation scenarios we assumed a continuation or even intensification of reduction measures. These reduction measures are assumed to be exclusively realized by end-of-pipe technologies.

Air pollutant emissions not coming from the energy sector (mainly NH_3 emissions from agriculture and emissions from industrial production) were obtained by multiplying activity levels of the respective sector from the IMAGE 2.1.2 model with sector specific emission factors. More details about the calculation of air-pollutant emissions can be found in section 2.5.

2.1 End use energy demand

The Energy Demand (ED) submodel of TIMER determines the demand for fuels and electricity in five sectors, namely industry, transport, residential sector, services, and others. The calculation of the secondary or end-use energy demand within each of these sectors is based on a number of dynamic factors:

1. The structural change of economies, such as shifts from heavy to light industry in the industry sector. This is formulated as a function of changing energy intensities (in GJ/$) depending on the per capita activity level within each sector and region.
2. Autonomous energy efficiency improvements (AEEI) account for price-independent technology development of new equipment in the different sectors. This factor considers that investments are made in the newest technologies which usually leads to a decreasing energy intensity.
3. Price-induced energy efficiency improvements (PEEI) reflect the technological improvements driven by increasing energy prices; PEEI is modeled by a “learning curve” where the rate of learning depends on the initial conditions and a progress ratio varying in time.
4. The share of secondary fuel type (electricity and non-electricity) which is based on the price and the useful energy conversion efficiency.

The main factors contributing to the uncertainty of calculating the demand for useful energy are listed in Table 2.1.

Table 2.1 Inventory of uncertainties of modeling energy demand

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	• Use of PPP-corrected GDP/cap or not • Relationship between useful energy and GDP/cap • Rate of change of AEEI[1] • Rate of change of PIEEI[2] • Secondary fuel substitution dynamics	• Use of PPP-corrected GDP/cap or not • Relationship between useful energy and GDP/cap • Rate of change of AEEI • Rate of change of PIEEI • Secondary fuel substitution dynamics
Parameters	• Learning curve coefficients • Activity growth elasticity • Fuel substitution determinants	• Learning curve coefficients • Activity growth elasticity • Fuel substitution determinants
Forcing functions	• Population • Economic activity levels (PPP)	• Population • Economic activity levels (PPP)
Initial state	Energy system capital stocks	/

[1] AEEI: Autonomous Energy Efficiency Improvement, [2] PIEEI: Price Induced Energy Efficiency Improvement

The most uncertain processes affecting energy consumption are the relationships between energy consumption, population, and economic power on the one hand and energy efficiency on the other hand. These relationships reflect the potentials for changes in consumer preferences and decisions for new technologies. Due to the long time horizon of the calculations (1990-2100) it is easy to imagine that these assumptions are highly uncertain.

Preliminary analyses, as part of a more comprehensive uncertainty analysis (Sluijs, 2000), indicate that the calculated energy demand is most sensitive to two factors: (1) the shape of the curve describing the so-called autonomous energy-efficiency investments (AEEI) and (2) whether a purchasing-power-parity-correction (ppp correction) on economic growth is applied or not.

Information about economic growth as well as population dynamics which are the main driving forces for energy demand were split up from the four world regions defined by the IPCC to the 17 regions of the TIMER model. In this step, the allocation of sectoral economic activity levels obtained from the WorldScan model (CPB, 1999) is more uncertain than the information about population dynamics.

One of the limitations of the setup of the energy model is that a feedback between macro-economic variables from the WorlScan model and the energy module TIMER are not taken into account. The activity level of the industry sector which is an important forcing function for energy consumption is e.g. not affected by changing fuel prices or investments to increase energy efficiency.

2.2 Electricity generation

The demand for electricity is calculated as a share of the total energy demand from the previous modeling step. It is fulfilled by fossil-fuel based thermal power, hydropower and a non-thermal alternative (solar, wind, nuclear). The share of these different ways of power generation is determined by the current situation for energy production (i.e. existing power plants), the assumptions made about the prices for secondary fuels and learning rates. Thus, the non-thermal alternatives for power generation penetrate the market based on their relative costs and a learning coefficient. These processes are simulated in the Electric Power Generation (EPG) submodel of TIMER. The main uncertainty factors of this modeling step are given in Table 2.2.

Table 2.2 Uncertainty of modeling electricity generation.

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	• Investment/fuel allocation	• Investment/fuel allocation
Parameters	• Learning curve coefficients • Fuel substitution determinants	• Learning curve coefficients • Fuel substitution determinants
Forcing functions	• Electricity demand	• Electricity demand
Initial state	/	/

The uncertainties of the EPG model results are mainly caused by assumptions about the future decisions for the technology used for electricity generation. How long do "old" technologies maintain, or, the other way round, how fast can new technologies be established. Modeling these decision processes for each of the 17 TIMER world regions needs assumptions about new investments in either old CO_2 intensive technologies or the development of new technologies.

Furthermore, the dynamics of factors which determine the share of different fuel types for electricity generation such as fuel prices and the availability of new technologies must be considered. However, assumptions about these factors are highly uncertain. Quantitative estimates of the relative contribution of these factors to the uncertainty of emission estimates of the TIMER model are not yet available.

2.3 Modeling primary energy use and production

The last step before the calculation of emissions is the modeling of the use of primary energy carriers to fulfill a regional energy demand. The share of different primary energy carriers within each sector and region is a function of the fuel price. In TIMER this price is governed by assumptions about fuel trade and by the availability of exploitable resources: Costs of exploitation rise with depletion of a resource and decrease with cumulated production due to learning-by-doing (supply cost curve) (de Vries et al., 2000). Accordingly, biofuels and other non-fossil alternatives can penetrate the market for liquid and gaseous fuels by a combination of fossil fuel resource depletion on the one hand and biofuel learning-by-doing on the other. The main uncertainties of this modeling approach can be found in Table 2.3.

Table 2.3 Uncertainties of modeling fuel supply.

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	• Fuel supply and trade	• Fuel supply and trade
Parameters	• Learning curve coefficients • Resource supply cost curve • Trade elasticities and constraints	• Learning curve coefficients • Resource supply cost curve • Trade elasticities and constraints
Forcing functions	• Fuel demand	• Fuel demand
Initial state	/	/

A dominant uncertainty factor with respect to primary energy use are the assumptions on the rate of technological progress reflected by the learning curves in different regions of the world.

A formal uncertainty analysis for the first one-region version of TIMER (TIME), however, indicated that the various feedback loops of the model tend to have a stabilizing effect, offsetting various uncertainties (de Vries et al., 1999). For instance, a higher learning coefficient in biofuel production causes faster substitution of oil and gas; this will slow down the depletion of the oil and gas resource base and hence the oil and gas prices decrease – which in turn slows down biofuel competitiveness.

2.4 Greenhouse gas emissions

In the final step of emissions modeling CO_2, CH_4, and N_2O emissions were calculated for each fuel in each sector and region by multiplying primary energy consumption with fuel-dependent emissions factors. Hence, in this step the driving force fuel demand stemming from the previous modeling step and the emission factors of the respective greenhouse gas are to be named as uncertainty factors (see Tab. 2.4).

Table 2.4 Uncertainties of modeling greenhouse gas emissions (CO_2, CH_4, N_2O)

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	/	/
Parameters	• Emission factors	• Emission factors
Forcing functions	• Sector-specific energy demand	• Sector-specific energy demand
Initial state	/	/

The emission factors were taken from literature or were adjusted so that agreement was obtained between model results and data for regional and global historical emissions.

Obviously, total emissions are especially sensitive to the emission factors of the fuels accounting for the largest share within the fuel mix of a region.

The uncertainty of emission factors differs from region to region since the quality and availability of data from which the emission factors are derived are very different. It is easier to get reliable data about fuel quality and fuel consumption from industrialized countries than from countries of the developing world. The emission factors of these countries (or regions) are, therefore more uncertain than those of the industrialized countries. Accordingly, in the case of a rising energy demand of the developing world this uncertainty is of increasing importance when the effects of global emissions are to be investigated.

2.5 Emissions of air pollutants

In order to evaluate the combined impacts of climate change and air pollution additional scenarios have been developed for SO_2, NO_x and NH_3 emissions between 1990 and 2100. New SO_2 emission scenarios have been built for the regional and global scale since we take into account that SO_2 borne sulfate particles have a mitigating effect on climate change. Both, NO_x and NH_3 are very reactive substances and therefore only play a role for air pollution and eutrophication on a smaller scale. Emissions of these two gases have been calculated for the IMAGE regions Western Europe, Eastern Europe and the European part of the former Soviet Union (FSU).

In contrast to the impacts of greenhouse gas emissions the awareness of the environmental damage caused by air polluting species is already high in many countries of the world. In Europe, the Gothenburg Protocol (UN-ECE 1999) prescribes reduction levels for SO_2, NO_x, and NH_3 emissions up to the year 2010. Hence, between 1990 and 2010 the AIR-CLIM emission pathways for these gases are fixed by the reduction targets of the Gothenburg Protocol. After 2010, however, different emission levels are possible. For these emissions we assume that the Gothenburg level of emissions serves as a cap for emissions between 2010 and 2100. Different mitigated emission pathways after 2010 are realized by applying a reduction function on unmitigated baseline emissions obtained from the TIMER model (SO_2, NO_x) and a newly developed model for NH_3 emissions.

Unmitigated emissions

In principle, unmitigated emissions for all three gases have been obtained by multiplying activity levels of energy and industry sectors with emission factors. The SO_2 and NO_x energy emissions have been calculated by multiplying energy consumption with sector- and fuel-specific emission factors. In the TIMER model unmitigated SO_2 emissions also result from industrial processes such as production of sulfuric acid and copper melting. Industrial NO_x emissions stem from cement production, nitric acid- and NH_3 production. The activity levels of the industrial sectors are assumed to change proportional to the change of energy consumption in the respective industrial sector.

For NH_3 emissions a new model was developed which is based on activity levels for the sectors livestock farming, nitrogen fertilizer use, industry and others which are implemented in the IMAGE model (see Mayerhofer et al., 2001).

Mitigated emissions

For the mitigation of global SO_2 emissions we applied the so-called Pollutant Burden Approach (PBA) (Onigkeit and Alcamo, 2000). The philosophy behind this approach is that increasing environmental damages caused by SO_2 emissions induce a political decision to establish mitigation measures in a region. In Europe and some other regions this already happened in the past whereas for many other regions of the world this is expected to happen in the future. Once, the decision for mitigation measures is made an end-of-pipe emission reduction is emulated by applying a logistic function on the unmitigated baseline emissions obtained from the TIMER model. For the European SO_2 and NO_x emissions where the decision for mitigation measures was already made in the 1980's, we assumed a continuation of the Gothenburg reduction level for one set of scenarios (P-scenarios) and an intensification of the reduction level for a second set of scenarios (A-scenarios). For NH_3 emissions no mitigation measures have been implemented. The main uncertainties resulting from these methodologies for calculating unmitigated as well as mitigated emissions of all three gases are listed in Table 2.5.

Table 2.5 Uncertainty of modeling SO_2, NO_x and NH_3 emissions.

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	/	• No climate feedback (SO2)
Parameters	• Emission factors for unmitigated emissions (SO_2, NO_x, NH_3) • Rate of emission reductions (SO_2, NO_x)	• Emission factors for unmitigated emissions (SO_2, NO_x, NH_3) • Rate of emission reductions (SO_2, NO_x)
Forcing functions	• Energy consumption in regions outside Europe (global SO_2) • Fuel mix in regions outside Europe (global SO_2)	• Energy consumption in regions inside and outside Europe (SO_2, NO_x, NH_3) • Future fuel mix, technological development, and learning curves • Starting point for emission reductions due to environmental burden (global SO_2)
Initial state	• Base year emission estimate (SO_2, NO_x, NH_3)	• Base year emission estimate (SO_2, NO_x, NH_3)

To evaluate the uncertainty of air-polluting emissions it is useful to distinguish between emissions from the energy/industry sector and the agricultural sector.

Long-term estimates for the future *unmitigated energy emissions* of the AIR-CLIM study are derived from two variables, namely energy consumption and a sector- and fuel-specific emission factor. Consequently, the uncertainty of emissions is mainly determined by factors such as energy consumption, technological improvements and fuel mixes. These factors depend among others on political and economic decisions and a change of consumer preferences (Price et al., 1998). These aspects are extremely difficult to predict for all regions and therefore highly uncertain when assumptions about them are needed as input for a model.

For the emission factors, however, the situation might be somehow different for European SO_2 and NO_x emissions (and probably emissions of other highly industrialized regions) compared to emissions of the non-industrialized regions of the world. For the European SO_2 emissions from energy production quite reliable data exist since in the past fuel consumption as well as fuel quality (e.g. sulfur content) have been monitored throughout Europe for several years (Grübler, 1998). Based on these data it was possible to obtain reliable sector and fuel specific emission factors for the past and the present situation. The question, however, remains, how large is the uncertainty introduced by extrapolating these emission factors to the future.

The situation is even worse for SO_2 emissions of those regions outside Europe where up to now only limited emission inventories are available and thus only few reliable data exist about the relation between energy consumption and SO_2 emissions. Consequently, estimates for current emission factors that could serve as a robust basis for projecting emission factors to the future are missing. This error in the initial value increases the uncertainty of future emission factors for all regions of the non-industrialized world compared to the emission factors for European emissions.

The uncertainties are different for the *mitigated energy emissions* of the AIR-CLIM project. The original Pollutant Burden Approach is a stochastic approach which considers (1) the uncertainty of economic and population development and (2) that predicting a political decision for environmental protection measures is highly uncertain. A range of emissions is therefore calculated for each region. Due to the assumptions of the PBA, this range is much smaller for those regions where emission reduction measures have already been established (OECD Europe, USA, Japan, Canada) compared to those regions where emissions still show an increasing tendency (Latin America, China, Africa and others). For the latter we assume that the necessity to model a political decision substantially increases the uncertainty of results whereas for the first group of regions simply a continuation or even strengthening of already existing environmental protection measures is assumed. For these regions the uncertainty mainly comes from the unmitigated emission pathways and the reduction rates.

With respect to the purpose these scenarios are developed for, it is worth to mention that the overall level of long-term SO_2 emissions in Europe is expected to be very low. According to the Gothenburg Protocol, emissions have to be mitigated by at least 63% up to 2010 (compared to the 1990 level) and it is very probable that emissions remain at these low levels or even decrease up to 2100 since abatement technologies will be more easily available. Hence, the uncertainty of emissions in absolute values of Tg S will decrease with time, although the relative uncertainty does not necessarily change.

This is also valid for NO_x emissions from energy/industry which contribute most to the overall NO_x emissions. For these emissions the Gothenburg Protocol demands a reduction of 49% compared to 1990 emissions.

The source of uncertainty of NH_3 emissions is of a very different kind. Here, the majority of emissions comes from livestock farming and nitrogen fertilizer use. Since some of the biotic processes which contribute to the formation of NH_3 are not yet fully understood the uncertainty of emission estimates is relatively high compared to the uncertainty of emissions from technological sources such as power plants. This lack of knowledge is in addition to the uncertainty of measured data which are needed to estimate model parameters (i.e. to calibrate emission models). Additionally, NH_3 emissions are expected to remain high not only under the A1-scenario but also under the Gothenburg Protocol which demands a moderate decrease of 15% until 2010. This might be due to the fact that in contrast to the reduction of energy/industry emissions no well established measures are available for the reduction of agricultural emissions. With respect to the modeling of impacts the absolute uncertainty in terms of km^2 of forest ecosystems affected by eutrophication might be quite high.

3. Modeling climate change in Europe

The change of temperature and precipitation is together with concentration and deposition of air pollutants the main forcing function for the impact analyses of the AIR-CLIM project. The climate change in Europe induced by global greenhouse gas emissions and SO_2 emissions of the AIR-CLIM scenarios originates from the combined results of two climate models. The first model is the Atmosphere Ocean System (AOS) of the IMAGE 2.1.2 model. The AOS is a 2 dimensional model which produces mean zonal climate change (temperature and precipitation) in 10° latitudinal bands i.e. with a medium spatial resolution. The advantage of this model is that computation time remains acceptable when climate change is calculated on a yearly basis. The spatial patterns of temperature and precipitation change on a 0.5° longitude by 0.5° latitude grid scale (the spatial resolution needed by the impact assessment models) is provided by the second model, namely the output of one run of a general circulation model (GCM). These GCM results for changes in temperature and precipitation patterns are used to downscale the IMAGE AOS information. The downscaling process in addition to the uncertainties inherent to both models must be kept in mind when changed precipitation and temperature are used in other parts of the AIR-CLIM modeling framework. An inventory of uncertainty factors is given in Table 3.1.

Table 3.1 Factors contributing to the uncertainties of modeling climate change

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	/	• Ocean circulation patterns are fixed
Parameters	• Parameterization of processes causing the climate change patterns of the GCM • Method for downscaling of precipitation • Climate sensitivity	• Parameterization of processes causing the climate change patterns of the GCM • Method for downscaling of precipitation • Climate sensitivity
Forcing functions	• Global greenhouse gas and SO_2 emissions	• Global greenhouse gas and SO_2 emissions
Initial state	• Simulation of current temperature and precipitation patterns partly inaccurate	• Simulation of current temperature and precipitation patterns partly inaccurate

The uncertainties of climate change modeling are of a very different quality. Since climate is a long time and large-scale phenomenon, not all aspects of the climate system are already understood. Especially, the occurrence of drastic changes such as the change of the thermohaline circulation cannot be predicted with the IMAGE climate model.

A further factor contributing to the uncertainty of model results is the sensitivity of the global climate to increasing greenhouse gas concentrations. The Intergovernmental Panel on Climate Change (IPCC) quoted a range of temperature increase between 1.5 and 4.5°C for a doubling of the CO_2 concentration with a best-estimate value of 2.5°C. The temperature sensitivity of the IMAGE model lies well within this range at 2.4°C. However, it is easy to imagine that choosing a higher or lower climate sensitivity can substantially affect the outcome of the model experiments.

The combination of a dynamic climate model (IMAGE AOS) with the results of a GCM simulation run requires a downscaling of the coarser results of the AOS to the finer resolution needed for the impact assessment. Especially the downscaling of precipitation is uncertain. Using an additive scaling could lead to a negative precipitation in areas with a very small initial value. Using a multiplicative approach avoids this problem but here the changes on areas with a small initial precipitation value will remain very small. For the AIR-CLIM scenarios we used the relative precipitation scaling. For this way of scaling Alcamo et al. (1998) found slightly lower impacts on natural ecosystems compared to results where an additive scaling method was used.

Spatial explicit climate data are needed for all impact assessments of the AIR-CLIM project. The quality of climate change patterns delivered by the GCM are therefore of major importance. Unfortunately, the patterns of precipitation are extremely difficult to predict which makes all analyses using future precipitation highly uncertain.

In order to estimate where and to what extent climate variables differ we compared the results for temperature and precipitation change patterns of two different GCMs. As the standard GCM for computing the climate change patterns of all eight AIR-CLIM scenarios a run of the ECHAM4 model of the Max Planck Institute (Germany) was used (see Cubasch et al. (1992) and Voss, (1999)). In order to find out which results are robust and to identify the disagreements between the two GCMs we used results of the HADCM2 model (Hadley Center, UK) (Johns et al., 1997). The experiment showed that temperature patterns of the two climate models are more in agreement in 2100 than precipitation patterns. This was not very astonishing, since it is known that the calculation of the processes and feed backs involved in cloud formation are very difficult and that not all processes involved are fully understood (Parry, 2000). Nevertheless, there are also some agreements with respect to precipitation: Both GCMs show a decrease of yearly precipitation for Spain and Portugal and increasing precipitation for the Scandinavian countries, although with different intensity. From this experiment, we can conclude that there is a certain probability that in Southern Europe and especially in Spain a temperature increase will be accompanied by drier conditions. This was also found by (Parry, 2000) who compared the results of four different GCMs and found for all of them a substantial decrease of precipitation for Spain in summer. For the winter months the precipitation increases for two of the GCMs and decreases for the other two. The decreasing trend in summer, however, is so strong that the result is an overall decrease of precipitation for Spain. Despite of these agreements it seems to be very important to further improve climate modeling since temperature and precipitation are important driving forces for many phenomena related to global change.

4. Dispersion and chemical transformation of air pollutants

In order to calculate the impacts of air pollutant emissions on natural ecosystems in Europe it was necessary to have air pollutant concentrations and depositions on a 0.5° by 0.5° grid scale. The air pollutant emissions for the eight AIR-CLIM scenarios, however, were calculated by the TIMER model on a regional basis (Western Europe, Eastern Europe and European part of the former USSR). These regional emissions must be scaled down to country emissions and source-receptor matrices (SRMs) were applied to calculate grid-scale atmospheric concentration and deposition of air pollutants from the 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 deposition 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 1996 (see Barrett and Berge, (1996)) for a further description of LADM). Within the AIR-CLIM project the air pollution concentrations and deposition in Europe have been calculated with monthly and annual SRMs.

Climate change will probably lead to long-term and seasonal changes in weather patterns and these changes may, in turn, alter the dispersion, chemical conversion and removal of pollutants in the atmosphere. One task within AIR-CLIM was, therefore, to model air pollution in Europe under changed climate conditions. For this purpose climate-dependent SRMs were derived by running LADM with meteorological data from the climate model ECHAM4 (Cubasch et al., 1999).

Six-hourly data were calculated for two timeslices with the ECHAM4 GCM: 1971-1980 (control period) and 2041-2050 (future period). In the future period the CO_2 concentration is doubled relative to pre-industrial levels and the global temperature rises by about 2°C compared with the control period. LADM was run for these two decades (1971-80 and 2041-50) using the 1996 EMEP S and N emissions for all years. Therefore, all differences between the results for the two timeslices are only due to changes in the meteorological data.

To apply the SRMs for the two timeslices in the AIR-CLIM project they have to be interpolated for different scenarios and years. For this interpolation parameters have to be used that are available from IMAGE 2.1.2, restricting the choice to temperature and precipitation. As precipitation is calculated in a different way in IMAGE than in ECHAM4, the average temperature in the EMEP area is used to linearly interpolate the SRMs between the future and the control period to calculate the SRM for a specific scenario and year.

Table 4.1 Factors contributing to the uncertainty of deposition and concentration of acidifying pollution under climate change (modified from (Alcamo and Bartnicki, 1987));

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	• Linearity	• Linearity • Changed weather pattern not taken into account[1] • Choice of interpolation parameter[2]
Parameters	• Parameter estimation errors	• Parameter estimation errors
Forcing functions	• Spatial distribution of emissions • Total country emissions • Meteorological inputs	• Future emissions (region and country) • Interannual meteorological variability • Uncertain meteorological changes under climate change[2]
Initial state	• Initial and boundary condition estimation errors	• Future initial and boundary conditions
Model operation	• Trajectory estimation errors • Solution of concentration equations • Processing of meteorological data	• Trajectory estimation errors • Solution of concentration equations

[1] only applies when standard approach (i.e. source-receptor matrices (SRMs) for present meteorology) is used, [2] only applies when interpolated climate-changed SRMs are used

Various parts of the method contribute to the uncertainties of the air pollution levels calculated for a given set of emissions: (1) how well LADM calculates the levels for given S and N emissions, (2) what errors are added by using SRMs instead of LADM for another set of emissions (linearity question), (3) what errors are incurred by applying the present SRMs for a changed climate or by applying the interpolated climate-changed SRMs.

Analyses have shown that LADM reliably reproduces the pattern of transboundary acidifying pollution in Europe (Tarrasón et al., 1998). In general, it is accepted that over long time and space scales the assumption of linearity between SO_2 emissions and deposition is appropriate (see Alcamo et al., 1987). The composite uncertainty of total deposition ranged from 10 to 20% in an uncertainty analysis of modeling long-range transport of sulfur in the present climate with the present SRMs (Alcamo and Bartnicki, 1990). This was less than the sum of individual uncertainties and indicated a compensation of errors. Thus, the use of a linear source-receptor matrix instead of the full model can be justified. The error for nitrogen could be larger, however, it has never been investigated in detail.

When the present SRMs are used to calculate air pollution levels under climate change, an additional error is incurred as changed weather patterns are not taken into account. The sensitivity analysis with the available climate-changed SRMs shows that this error seems not significant averaged over large regions. But, while the various GCMs agree rather well with respect to the global average temperature, they differ significantly for precipitation and for regional climate (Houghton et al., 1995). Thus, it would be of special interest to see what the results based on meteorology from another GCM would be. Another issue is what error is made by interpolating the SRMs for the future and the control period for other scenarios and years.

5. Impact studies

In this section the main uncertainties of the three kinds of studies dealing with the impacts of air pollutant and greenhouse gas emissions are compiled and discussed. In particular, we present where the uncertainties of the critical values for air pollutant deposition, air pollutant concentration and climate change come from. Further, the uncertainties of the final results of the AIR-CLIM study, namely the exceedance areas for ecosystem impacts are evaluated.

5.1 Calculation of climate-dependent critical loads

Critical load values for sulfur and nitrogen are widely accepted as a basis for policy decisions dealing with the protection of natural ecosystems against acidification and eutrophication. However, these critical loads were developed for present climate conditions. For the AIR-CLIM study new critical loads were calculated for European forest ecosystems under changing climate conditions.

The steady-state Simple Mass Balance (SMB) model was used to calculate the critical loads of acidifying sulfur and nitrogen as well as nitrogen as a nutrient causing eutrophication of soils when available in excess (Posch, 2001). The SMB model calculates the charge balance for the major ions in the soil solution for a large number of soil and forest types in Europe. If the deposition of acidifying or nutrifying substances is higher than the ecosystem-specific buffer capacity for acidification or nutrification we call this an exceedance of the critical load. In the SMB model this buffer capacity is determined by the dynamics of the base cation concentration and the critical leaching of acid neutralizing capacity including the release of aluminium. A change of temperature and precipitation influences the buffer capacity in three ways: (1) An increasing temperature increases the weathering rate of base cations which leads to a higher critical load and the ecosystem becomes less sensitive. (2) To cover a change in precipitation the so-called percolation (=precipitation minus evapotranspiration) is the relevant factor. An increase of precipitation increases the leaching of acid neutralizing capacity if the evapotranspiration remains constant. For this case the critical load is decreased and a forest ecosystem becomes more sensitive. However, a changing precipitation often accompanied by an increase of temperature so that the relationship becomes more complex. (3) Changing climate conditions affect the growth rates of forests which has an influence on the uptake rates of any kind of nutrients. This factor could either increase or decrease the critical loads depending on the suitability of the new climate for the forest ecosystem of a certain site.

All these factors have been considered, but nevertheless, a large number of simplifications had to be made to perform the critical load calculations on the European scale. The main uncertainties introduced by simplifications but also by a lack of knowledge about the very complex ecosystem responses to air pollutant deposition are given in Table 5.1.

Table 5.1 Uncertainties of calculating climate-dependent critical loads for acidifying and nutrifying substances

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	• Modeling of aluminium chemistry (complexation with organic acids)[acid] • Link between chemistry and plant response (aluminium-base cation ratio)[acid]	• Modeling of aluminium chemistry (complexation with organic acids) • Link between chemistry and plant response (aluminium-base cation ratio) • Land use change not considered [both]
Parameters	• Immobilization of nitrogen [both] • Weathering of base cation [acid] • Critical leaching of N [nut]	• Immobilization of nitrogen [both] • Weathering of base cation [acid] • Critical leaching of N [nut]
Forcing functions	• Base cation deposition (assumed to be constant)[acid]	• Base cation deposition [acid] • Future climate data [both]
Initial state	• Soil map[both] • Forest cover and type[both]	/

Acid, nut, both stands for the type of critical load that the listed uncertainty is relevant for: Acidification, nutrification or both types of critical load.

The critical loads concept is used since almost two decades for studies in a variety of different countries and regions of the world. But it is just now that the first systematic uncertainty analyses about the effects of the uncertainty of critical loads have been published. (Syri et al., 2000) and (Suutari et al., 2001) evaluated the uncertainty of critical loads as part of a more comprehensive analysis which covered the whole cause-effect chain from air-pollutant emissions to ecosystem protection in Finland and Europe, respectively. (Syri et al., 2000) found that for most parts of Finland the uncertainty of critical loads for acidification dominates the overall uncertainty of the modeling exercise and states that further research efforts should focus on a more precise description of ecosystem responses. This leads to the often mentioned critique that a steady-state critical load approach like that used for the AIR-CLIM study is not appropriate for the evaluation of future acidification problems with a more than 100 year time horizon. The use of the static approach, however, can be justified by the large amount of highly disaggregated input data and parameters needed by dynamic ecosystem models. Since these data are not or only partly available new simplifications would have to be introduced which would lead to new sources of uncertainty. On the long term, however, the use of dynamic models should be strived for.

Two sensitivity analyses of parameters affecting the critical load for nutrient-N were performed within the AIR-CLIM project (Posch, 2001) since these critical loads are mostly affected by biotic factors which are highly uncertain. Additionally, the results of the AIR-CLIM analysis show that the critical load for nutrient N remain exceeded on substantial areas until the end of the century. This is in contrast to the results for the acidification of forest ecosystems which might substantially decrease until 2100.

A key parameter in the critical load of nutrient N is the acceptable N leaching concentration, which links soil solution chemistry to undesired changes in vegetation. To investigate the sensitivity of critical load for nutrient N exceedances to this parameter calculations were carried out with a maximum acceptable N concentration in the soil solution of 0.2 and 0.4 gN/m^3, thus bracketing the value of 0.3 used for the AIR-CLIM scenarios. It should be noted that 0.4 represents an upper limit recommended (UBA, 1996). Obviously, the higher the acceptable concentration, the less sensitive the ecosystem and the smaller the area exceeded. We found that the maximum deviation from the standard run is about 5% of the forest area in 2010, and this number is decreasing over time.

Another highly uncertain parameter is the net amount of nitrogen that can be sustainably stored (accumulated) in forest soils. Although the value of 1 kgN/ha/yr, used in the analysis, is at the upper end of recommended values, current rates of N immobilization are much higher and it could be argued that under climate change, when more carbon is sequestered, also more nitrogen could be stored in forest soils without imbalancing C:N ratios. Thus, the effect of using 2 kg/ha/yr on the area were critical loads are exceeded was investigated. The increase from 1 to 2 kgN/ha/yr causes a reduction in the area exceeded between 10% (in 2010) and 5% (in 2100) for critical loads of nutrient N, whereas for acidity critical loads, which also depend on the N accumulation rate the effect is much smaller (about 1% change in exceeded area).

5.2 Areas where critical loads are exceeded

In order to calculate the exceedance areas for critical loads of acidity and nutrient nitrogen the amount of acidifying substances and nutrifying nitrogen deposited to the different forest ecosystems within each 0.5° by 0.5° grid cell is compared to the critical loads of these ecosystems. If the amount deposited is greater than the critical load value for acidity (combined critical load function for S and N) or nutrient N we call it an exceedance of critical load.

The extent of critical load exceedance within each grid cell is calculated by the so-called average accumulated exceedance (AAE) which is defined as the weighted average of individual exceedances in a grid cell. The amount of exceedance is defined via the combined reduction of sulfur and nitrogen deposition which is necessary to reach an acidifying deposition below the critical load for acidity. This level can either be reached by reducing only N deposition or only S deposition. However, a more feasible way is the combined reduction of S and N which is *defined* as the shortest path between actual depositions and the combined critical load functions of S and N (for more details see (Posch, 2001)).

Table 5.2 Uncertainty factors of calculating areas where critical loads are exceeded.

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	- Definition of exceedance $(AAE)^{acid}$	- Definition of exceedance $(AAE)^{acid}$
Parameters	/	/
Forcing functions	- Patterns of deposition for sulfur and nitrogen - Critical loads	- Patterns of deposition for sulfur and nitrogen - Critical loads
Initial state	/	/

The final step of the impact analysis for critical deposition of acidifying and nutrifying substances is based on a large number of model outputs as there are emissions of SO_2, NO_x and NH_3 as well as deposition of these substances, critical load calculation and finally the linking of all model results in the final step of calculating exceedance areas. Uncertainties of all these modeling steps contribute to the overall uncertainty of the impact level. However, in the case of acidifying depositions it is highly probable that deposition levels decrease because of decreasing emissions. The consequence is that the impact levels for acidification (i.e. the area with critical load exceedance) will also substantially decrease so that the uncertainties of these emissions will decrease in time in absolute terms of km^2 exceedance area. This was also found by (Syri et al., 2000) who estimated the uncertainty of critical load exceedances in Finland.

The situation is somehow different for the problem of soil eutrophication where biotic emission sources play an important role. For these sources emissions estimates are much more uncertain than for emissions from more technical processes such as power generation and industrial production. Furthermore, deposition levels remain quite high throughout the scenario period (Posch, 2001). Further quantitative uncertainty estimates should therefore focus on the nutrifying N depositions and their impacts.

5.3 Calculation of climate-dependent critical levels

The damage that air pollutants might cause in natural ecosystems mainly depends on the ambient concentration of this pollutant but also on its flux into the single plant. This flux into the plant can be described by the stomatal conductance which is governed, among other factors, by temperature and water conditions. Critical concentrations which are defined by the UN/ECE Convention on Long-range Transboundary Air Pollution (LRTAP) for annual means or half year means of SO_2 and NO_x concentrations are meant to protect ecosystems when the concentration of an air pollutant remains below this critical value. Within the AIR-CLIM project a simplified conductivity model was applied to quantify the response of forest ecosystems in Europe to future SO_2 and NO_x concentrations under changing climate conditions (Guardans, 2001). The model was used to calculate the change of the prescribed critical concentrations for trees, or in other words their change in sensitivity due to climate change. The response of two types of tree species was estimated as representatives of deciduous and coniferous forests in Europe. The uncertainties inherent in this modeling approach are listed in Table 5.3.

Table 5.3 Uncertainty factors of calculating climate dependent critical levels

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	• Independence of different response functions • No history or memory • No adaptation	• Independence of different response functions • No history or memory • No adaptation
Parameters	• CO_2 response of stomatal conductance • Monthly SO_2 critical level	• CO_2 response of stomatal conductance • Monthly SO_2 critical level
Forcing functions	/	/
Initial state	• Simplified representation of land cover and type	• Simplified representation of land cover and type • No land cover change

A number of simplifications had to be made to quantify the impacts of temperature and precipitation change on the critical air pollutant concentration.

First, the stomatal conductance model which serves as a basis of the simulation assumes that the response of the plant to one variable (e.g. temperature) is independent of its simultaneous response to other variables (e.g. water vapor pressure deficit). This is a simplification which can result in non linearities in the response of the model. Another problem of the simple first order multiplicative model is that the response of the plant at one point in time is assumed to be independent of the previous state of the plant. A similar aspect is that calculations are made for a long time into the future but the model assumes no adaptation of the plants.

Another factor contributing to the uncertainty of the results is that the critical concentrations obtained from LRTAP are defined for annual mean or half year mean concentrations whereas the model calculates changes of critical concentrations on a monthly basis.

A further source of uncertainty is the simulation of the effects of an increasing CO_2 concentration on the stomatal conductance. A very simple approximation based on (Jarvis et al., 1999) assumes that a doubling of CO_2 concentration levels would produce a

20% decrease in stomatal conductance. To explore the impact of this assumption a model run was performed assuming no CO_2 effect. The result of this experiment is that especially areas in Northern Europe become more sensitive to air pollution when the climate conditions are going to change and the mitigating effect of a higher CO_2 concentration is neglected.

5.4 Areas where critical levels are exceeded

The critical levels for two types of ecosystems which were calculated in the previous modeling step were now used to estimate those areas where the critical levels are exceeded under the different AIR-CLIM scenarios. In other words, patterns of air pollutant concentrations were calculated for each scenario and compared to the critical levels within each grid cell. The air pollutant concentration within each grid cell was computed with the source-receptor matrices (SRM) derived from the EMEP long-range atmospheric transport model. The main uncertainties of this approach are listed in Table 5.4.

Table 5.4 Uncertainty factors of calculating areas where the critical level is exceeded

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	/	/
Parameters	/	/
Forcing functions	• Patterns of air pollutant concentration • Critical levels	• (climate-dependent) patterns of air pollutant concentration • Critical levels
Initial state	/	/

For this modeling step the results of two sub models were used as input and thus determine the uncertainty of the results. These are (1) the way that the source-receptor matrices (SRM) were used to estimate the dispersion of future SO_2 and NO_x emissions and (2) the way that the critical levels were calculated. For the uncertainties inherent in these modeling steps the reader is referred to section 4 for the calculation of SRMs and section 5.3 for the computation of the critical levels.

5.5 Calculation of critical climate

To evaluate the potential effects of different global climate change scenarios on European ecosystems the so-called critical climate concept was developed. This concept considers the impacts of changing temperature and precipitation on the potential natural vegetation in Europe. The focus on natural ecosystems makes the results of the analysis comparable to the impacts of air pollution on ecosystems and helps to identify those ecosystems in Europe which might suffer from both problems in the future and which are therefore especially vulnerable. The 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”. This definition requires (1) the specification of an appropriate ecosystem related indicator and (2) the decision for a climate change impact on natural ecosystems that is acceptable. For the purpose of this project we used the decrease in net primary productivity (NPP) as an indicator because it is sensitive to climate change and additionally large scale ecosystem models are available that calculate NPP of natural ecosystems as a standard variable. For the AIR-CLIM project we used the BIOME3 model (Haxeltine and Prentice, 1996) in order to estimate a change in NPP as the main indicator but also the climate induced change of a biome type as a second indicator. BIOME3 calculates the productivity of each plant functional type as a function of photosynthetic activity and leaf area index. As an acceptable effect of climate change we defined a 10% NPP decrease of natural ecosystems. For a more detailed description see (van Minnen et al., 2001). The sources of uncertainty introduced by this way of calculating critical climate is summarized in Table 5.5.

Table 5.5 Uncertainties of the calculation of the critical climate.

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	• Effects of air pollution on plant physiology • Aggregation of plant functional types	• Effects of air pollution on plant physiology • Changed patterns for pests and diseases and/or fire events • Mean climate change used instead of climate variability • Aggregation of plant functional types • Adaptation of ecosystems
Parameters	• Parameters of photosynthesis calculation • Parameterization of evapotranspiration • Parameters for root distribution	• Parameters of photosynthesis calculation • Parameterization of evapotranspiration • Parameters for root distribution
Forcing functions	/	/
Initial state	• Soil data • Type of potential natural vegetation	• Soil data • Type of potential natural vegetation

The assumed acceptable productivity loss of 10% caused by climate change can be easily an underestimation of ecosystem productivity under future climate conditions due to the exclusive focus on temperature and precipitation change. Indirect impacts of climate change such as changed patterns for pests and diseases but also a changing frequency of fire events is not yet considered. The simplified approach, however, is reasonable since quantitative information about additional impacts is not yet available or also highly uncertain.

Additionally, the 10% limit seems quite low since it is not known whether the uncertainty of NPP calculations with the BIOMe3 model is of the same order of magnitude. Especially, from this point of view the acceptable effect needs further investigation.

A further source of uncertainty is the level of aggregation of ecosystem types which are assumed to respond homogeneously to changing climate conditions. It is not clear, however, to what extent and direction a higher resolution would change the scenario results.

The design of the scenario study does not consider the history of a certain type of vegetation but only looks at one point in time which is characterized by the response of the current potential natural vegetation to a temperature and precipitation change. Thus, we don’t consider the ability of the natural vegetation to adapt to changing climate conditions.

With respect to the uncertainty of model parameters Hallgren and Pitman (2000) found that NPP values of the BIOME3 model were especially sensitive to the parameterization of photosynthesis. But also small changes of the parameters for evapotranspiration and root distribution have a considerable effect on the NPP of a certain biome type. Since a change of biome type is induced by a changing NPP these parameters have also an effect on the initial biome type which is used as a reference for a decrease of NPP.

5.6 Areas where critical climate is exceeded

In the final step of the climate impact assessment the climate change information of the eight AIR-CLIM scenarios has been used to evaluate where in Europe the critical climate for ecosystems will be exceeded between 1990 and 2100. This is simply done by comparing the projected change in temperature and precipitation of each 0.5° by 0.5° grid cell with the critical climate of this grid cell. The result of this analysis is the exceedance area for critical climate in km² or percent of Europe’s area.

Table 5.6 Factors contributing to the uncertainty of the exceedance areas for critical climate change

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	/	/
Parameters	/	/
Forcing functions	/	• Temperature and precipitation of the climate change scenarios • Critical climate
Initial state	/	/

For the final step of the climate impact analysis the only factors contributing to the uncertainty of the results are the information about temperature and precipitation change and the critical climate value for each grid cell. The uncertainty of the critical climate values has already been discussed in the previous sections whereas the uncertainties of the climate change simulations can be found in section 3.

6. Cost calculations

The cost estimates for the mitigation of greenhouse gas emissions and air pollutant emissions were performed in a different way. In order to reduce global greenhouse gas emissions the price mechanisms included in the TIMER model were used to induce technological improvements and shifts to less carbon intensive energy production. For the mitigation of air pollutant emissions a more technology oriented approach was chosen, in that the price of end-of-pipe technologies determines the costs of emission reductions.

6.1 Mitigation costs for greenhouse gas emissions

The main instrument used to construct mitigation scenarios which lead to a stabilization of the atmospheric CO_2 concentration is the introduction of a world-wide uniform carbon tax. This carbon tax can be seen as a proxy of the total mitigation pressure on the energy system (see e.g. Criqui et al., (1999), van Vuuren (2001)). It is levied at the consumer end of the chain. Application of such a tax implies that the marginal costs in different regions are more or less equalized. Such a scenario is only feasible as result of close international cooperation, for instance in the form of emission trading. Application of the tax generates several responses in the model: A single carbon tax profile is introduced for all regions which initially rises linearly and is constant later on. It is adjusted until the resulting world carbon emissions from fossil fuel combustion equal a stabilization trajectory (den Elzen et al., 2001). The change in user costs, that is, the product of final energy carriers and their associated prices for consumers, reflects system-wide emission mitigation costs (see van Harmelen et al., 2001).

Table 6.1 Uncertainties of calculating costs for greenhouse gas emission mitigation.

	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	/	• One carbon tax for all regions
Parameters	/	• All price induced changes of technology and fuel mix
Forcing functions	/	• Baseline emissions
Initial state	/	/

First of all, the assumption of one single carbon tax for all regions seems to be a rough simplification which makes the costs of European emission reductions highly uncertain. However, according to the underlying IPCC storyline the A1- and the B1-world are both worlds with a high degree of globalization. A worldwide cooperation in mitigating emissions is thus more plausible in these two worlds than e.g. in the IPCC scenarios A2 or B2. Consequently, the model inherent mechanisms induced by the carbon tax, namely highly effective emission reductions by emissions trading, acceleration of global technological development by transfer of knowledge and technology and other processes seem to be feasible but nevertheless highly uncertain.

However, because of the assumed openness of the A1 and B1 world the missing of macroeconomic feedbacks could play an important role for the calculation of mitigation costs.

The discussion of the uncertainties of unmitigated or baseline emissions which determine the amount of emissions that must be reduced can be found in section 2.4.

6.2 Mitigation costs for air pollutant emissions

In contrast to the mitigation of greenhouse gas emission the reduction of SO_2 and NO_x emission is realized by end-of-pipe technologies such as Flue Gas Desulphurisation to reduce SO_2 emissions of power plants or three-way catalysts to reduce NO_x emissions from cars. Consequently, the price and the market penetration of these cleaning technologies determine the costs of emission reductions. However, the costs also depend on the reduction level already achieved. Marginal cost curves have been used to calculate costs by identifying a least cost package for each reduction unit within each sector and for each fuel type. The investment costs for a certain abatement technology are specified on the global level as we assume a high level of globalization for the AIR-CLIM scenarios (see van Harmelen et al., 2001). The main uncertainties and limitations of this approach can be found in Table 6.2.

Table 6.2 Uncertainties of calculating mitigation costs for SO_2 and NO_x emissions.

Type of uncertainty	Diagnostic (past/current)	Prognostic (scenario analysis)
Model structure	• Interaction between measures • Mechanical approach (no behavior)	• Cost optimal behavior • No feedback between costs of add-on cleaning technologies and the energy system • No learning curve in terms of technological properties or costs
Parameters	• Cost curve parameters	• Interest rate remains constant over time and equal for all regions • Park properties (operation hours and average installed capacity) • Technology parameters • Resource costs per region
Forcing functions	• Present emissions	• Unmitigated future emissions • Regional emission reduction objective (PBA)
Initial state	• Present emissions • Present state of the art technology properties including costs • Abatement technology already implemented	

The calculation of abatement costs for air pollutants is a purely technology driven approach and provides the minimum costs for reaching a reduction objective obtained by the pollutant burden approach. But it is conceivable that decisions for a certain reduction technology are driven by other options than costs which could also lead to higher cost.

A further uncertainty is introduced by neglecting the cost effects of learning by doing; all technologies have the same price throughout the whole scenario period. An overestimation of costs could be the consequence of this simplification.

The main parameter uncertainties stem from limited technological information about removal efficiency, investment cost functions and economic lifetime of a certain abatement technology. Additionally, the demand and the costs for resources such as labor, sorbents, catalysts and disposal are fraught with uncertainty.

Furthermore, the fuel mix is prescribed by the TIMER model and there is no feedback between the costs of applying abatement technologies and the fuel mix. The exclusive application of add-on technologies to reach a reduction objective instead of a mixture of measures must be seen as a limitation of the whole approach.

7. Summary and conclusions

This inventory presents an overview of the main uncertainties of the AIR-CLIM modeling framework according to the view of the scientists who developed and/or applied the models. Partly quantitative estimates of model uncertainties are available, however, only for single components of the framework and for them mainly the effects of parameter uncertainties have been investigated. The effects of e.g. using different modeling approaches within a comprehensive uncertainty analysis are very difficult to obtain since commonly used techniques such as the Monte Carlo simulation for parameter uncertainties are hardly available for this type of uncertainty.

With respect to the uncertainty of the results of the modeling framework three aspects should be emphasized because they are of main importance for the overall uncertainty of the AIR-CLIM results:

The first issue is the modeling of energy consumption and technology change which is strictly spoken a modeling of human behavior. Consequently, the translation of economic and population data into energy consumption and finally greenhouse gas emissions is a highly uncertain matter. However, the energy and emissions model already considers a kind of adaptation to changing availability of resources or technologies. These so-called learning curves, although far from being certain they introduce an adaptation mechanism which represents an advantage of this kind of models in contrast to most of the models dealing with the response of ecosystems to changing environmental conditions.

The second point to be mentioned is the way of modeling the ecosystem response to a changing climate. Impacts of climate change are difficult to model since they are much more difficult to measure than the main climate variables like temperature and precipitation. Hence, a reliable data basis for modeling e.g. a forest ecosystem response to climate change is up to now not available. With respect to the long time scale of typical climate change scenarios the question of adaptation of ecosystems could play an important role but is extremely difficult to model.

A third aspect which contributes to the uncertainty of the AIR-CLIM results is the difference in data availability and data quality between the industrialized world and the developing world. These data are needed to model the principle relationship between driving forces and to estimate the parameters of the resulting model. Within the AIR-CLIM project this plays an important role for both the energy related issues and the climate change aspect. But since small changes in e.g. per capita income in these regions could have a large effect on the global climate system it is very important to better know the processes leading to e.g. their technological changes. The assumption that these regions simply follow the behavior of the industrialized world (only with a delay in time) is often used but this is possibly a rough oversimplification of processes. It is only justified in the AIR-CLIM study because a high level of globalization is assumed for the two base scenarios. Nevertheless, it remains of importance to obtain more reliable data to adequately model e.g. the processes of energy consumption and technological change in developing countries.

In general it can be said that the more steps are involved to obtain a model result the more uncertain are the results. This is especially true if a very uncertain aspect appears very early in the chain of models. This is for example the case for the modeling of precipitation changes which is highly uncertain but is a very important driving force for all impact categories of the AIR-CLIM study.

However, this listing of the most uncertain model aspects should be regarded with caution. Some preliminary analyses of e.g. the energy model TIMER have shown errors that compensate for each other so that the results of a modeling exercise remain quite robust even if parameters are varied. It is therefore very difficult to rank uncertainty factors based on a more or less qualitative uncertainty analysis as it is presented in this report. However, the report underlines the importance of such a systematic and quantitative evaluation since models can be a valuable tool to investigate very complex and policy relevant issues. Additionally, this report can serve as a basis for quantifying the uncertainty of the whole modeling framework since it helps to identify those parameters and processes within the sub models which should be considered in an evaluation of the overall uncertainty of the modeling framework.

Acknowledgments

The work presented in this paper is carried out as part of the AIR-CLIM project. AIR-CLIM is funded by the European Commission, Directorate General XII within the EC Environment and Climate Research Programme (1994-1998), Contract No. ENV4-CT97-0449.

8. References

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