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

Summary Final Report

J. Alcamo (Editor)

Center for Environmental Systems Research, University of Kassel
Kassel, Germany

National Institute of Public Health and the Environment (RIVM)
Bilthoven, The Netherlands

Centro de Investigaciones Energeticas Medioambientales y Tecnologicas (CIEMAT)
Madrid, Spain

TNO-MEP
Apeldoorn, The Netherlands

EC Environment and Climate Research Programme (1994-1998)
Research Theme 4: Human Dimension of Environmental Change

Summary Final Report

Contract No.: ENV4-CT97-0449

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

Key Words: air pollution; climate change; climate thresholds; critical loads; critical levels; emission scenarios; integrated assessment; source-receptor matrices

Reporting Period: 1 January, 1998 to 31 December, 2000

Project Coordinator: Joseph Alcamo
Project Manager: Petra Mayerhofer

Partners

1. **Center for Environmental Systems Research, University of Kassel**
Kurt-Wolters-Str. 3, D-34109 Kassel, Germany. Tel.: +49 561 804-3898, Fax: 804-7266, Email: airclim@usf.uni-kassel.de.

   Co-Coordinators for Kassel: Joseph Alcamo and Petra Mayerhofer
   Further project members: Jelle van Minnen (up to February 2000), Janina Onigkeit

2. **Laboratory for Assessment of the Environment and Natural Resources, National Institute of Public Health and the Environment (RIVM)**
Antonie van Leeuwenhoeklaan 9, NL-3720 BA Bilthoven, The Netherlands. Tel.: +31.30.274-3529, Fax: 274-4435, Email: jean-paul.hettelingh@rivm.nl.

   Coordinator for RIVM: Bert de Vries
   Further project member: Maximilian Posch, Detlef van Vuuren, Michel den Elzen, Jelle van Minnen (from March 2000 on)

3. **Departamento de Impacto Ambiental de la Energia, Centro de Investigaciones Energeticas Medioambientales y Tecnologicas (CIEMAT)**
Av. Complutense 22, E-28040 Madrid, Spain. Tel.: +34.1.3466-174, Fax: 3466-005, Email: guardans@ciemat.es.

   Coordinator for CIEMAT: Ramon Guardans
   Further project member: Benjamin S. Gimeno

1 OBJECTIVES

Up to now the large scale environmental issues of regional air pollution and climate change in Europe have been analyzed almost entirely independently of one another, both scientifically and politically. This is not entirely surprising since the impacts of regional air pollution were identified decades ago, whereas climate change impacts have been anticipated but not observed until recently. Moreover, climate change requires global policy action, whereas regional air pollution in Europe can more or less be solved by agreements between European countries alone. But now climate change is claiming a higher and higher place on the scientific and policy agendas of Europe, and it has become important to understand the connection between these two problems. Therefore, the AIR-CLIM Project was carried out to assess the linkages of regional air pollution and climate change in Europe. The objectives of the project were to address the following main questions:

- Over the long run, what will be the relative importance of regional air pollution and climate change in Europe?
- What are the possible linkages between regional air pollution and climate change in Europe's environment, in particular
  - How will climate change affect the distribution of regional air pollution in Europe?
  - How will climate change affect the sensitivity of European ecosystems to regional air pollution?
  - How will regional air pollution in the form of sulfate aerosols affect climate change in Europe?
- What will be the impact of climate policies on the costs of controlling regional air pollution?

2 METHODOLOGY: THE AIR-CLIM APPROACH

2.1 Integrated Approach and Modeling Framework

To address the complex research questions addressed in the AIR-CLIM Project, an "integrated approach" was taken. This involved the following steps: (1) formulating more precisely the research questions, (2) identifying the integrated system to be studied, (3) assembling and linking models as a research tool in the form of a "modeling framework" (see next paragraphs), (4) deriving scientifically-relevant results, policy-relevant results, and policy messages, and (5) identifying gaps in knowledge and need for research.

The basic research tool used in the project was an "integrated modeling framework". This framework was *integrated* in that it covered and linked key elements and components of the problems (economy, emissions, atmospheric processes, and terrestrial impacts), and because it addressed long time scales, and all of Europe.

The framework is made up of components of two existing integrated models, RAINS and IMAGE 2 (Figure 1). RAINS (*R*egional *A*cidification *IN*formation and *S*imulation) is an integrated model of acid deposition in Europe which links energy scenarios with their production of country-scale emissions of sulfur, nitrogen and oxidant precursors. Based on computed emissions, the model computes resulting ambient concentration and deposition of acidifying substances and compares the deposition with critical loads to ecosystems. The IMAGE 2 model (*I*ntegrated *M*odel to *A*ssess the *G*reenhouse *E*ffect) is RAINS' counterpart for global climate change, and links regional-scale changes in energy use and agricultural production with emissions of greenhouse gases, oxidant precursors, and sulfur dioxide. Using a climate model of intermediate complexity, IMAGE 2 calculates the build-up of greenhouse gases in the atmosphere and the resulting change in precipitation and temperature. It also calculates changes in land cover based on socio-economic and climatic factors, and the carbon fluxes between the biosphere and atmosphere. Figure 1 shows the components that were linked to make up the AIR-CLIM modeling framework.

[Figure 1. The AIR-CLIM modeling framework]

2.2 Indicators

In order to make the study of regional air pollution and climate change manageable, it was necessary to focus on a limited number of sub-problems and indicators. For climate change, the obvious choices were changes in surface temperature and precipitation because of the large number of potential impacts associated with these parameters. It was more difficult to select indicators for regional air pollution because of the large number of substances that play a role in this problem in Europe. In the AIR-CLIM Project it was decided to focus on acid deposition and nitrogen deposition with some attention to air concentrations of nitrogen oxides (NO_x) and sulfur dioxide (SO_2). One reason is that their precursor emissions have been controlled in Europe by a series of international agreements (for example, the international treaty to "Abate Acidification, Eutrophication and Ground-level Ozone") and this raises the interesting question of whether climate change will affect any of the assumptions made about these pollutants (for example, the amount of one country's emissions being deposited in another). Moreover, knowledge about sulfur and nitrogen processes in Europe's environment is more advanced than for other regional pollutants, making them a natural starting point for an integrated analysis. An additional factor is that at least one regional air pollutant stemming from sulfur dioxide emissions in Europe (sulfate aerosol) has an established link to climate change (as explained later in the text). For these reasons we concentrate on sulfur and nitrogen. However, we recommend that other important regional air pollutants, e.g. persistent organic pollutants and oxidants, be given attention in any follow-up studies.

2.3 Scenario Analysis

One prerequisite for comparing regional air pollution and climate change is to generate a consistent set of emission scenarios based on a common set of driving forces (e.g., trends in population and economic growth). We take these driving forces from the so-called "SRES" scenarios ("Special Report on Emission Scenarios") of the Intergovernmental Panel on Climate Change (IPCC). These scenarios are used in AIR-CLIM because their development and review under the auspices of the IPCC has earned them a fair degree of international acceptance. Out of these scenarios we use Scenarios "A1" and "B1" because they have driving forces and emission levels that span much of the range of assumptions found in the literature on scenarios of greenhouse gas emissions. A main feature of these scenarios are their "storylines" which are narrative descriptions highlighting the scenarios' main features and the relationships between the scenarios' driving forces and main features.

- The A1 storyline describes a world in which globalization continues to be an important feature and in which economic development is rapid and successful in raising average incomes. Among other effects, higher incomes bring increasing ownership of private vehicles, greater urban sprawl, and denser transport systems. Society in the A1 world has a pragmatic view towards environmental protection and assumes that nature is very resilient to economic growth and development.
- In the B1 storyline the world also continues to globalize, but society assumes a strong commitment to environmental values and sustainable development. Priority is given to improving the efficiency of resource use which leads to substantial decreases in the amount of materials and energy needed per unit of service and product.

Consistent with these storylines, the IPCC assumed values for the driving forces of emissions, including population, economic growth, and the type and magnitude of energy production. However, the AIR-CLIM Project could not use the driving forces of the SRES scenarios in their original form because they were only available for large aggregated world regions. Hence in the AIR-CLIM Project we downscaled the assumptions of the IPCC to European sub-regions where possible, and made additional assumptions where necessary that were consistent with the storylines.

The AIR-CLIM version of the A1 and B1 scenarios show modestly increasing economic growth up to 2020 in Western Europe, and then a decline in the second half of the century to 1.6 percent per year in the A1 scenario, and 1.0 percent per year in B1. Meanwhile, vigorous economic growth (in terms of annual change in GDP per capita) is assumed for Eastern Europe and Russia in both scenarios (ranging from about 4 to 6 percent per year between 2010 and 2050). The growth rate in the A1 scenario is assumed to be somewhat higher than in B1. As for demographic trends, total population sinks slowly in Western Europe but rises gradually in Eastern Europe and Russia until around mid-century when it also begins to decline.

3 MAIN RESULTS

3.1 New Long-term Emission and Deposition Scenarios for Europe

AIR-CLIM is one of the first studies of any region in which detailed scenarios of both air pollution and greenhouse gas emissions were developed. It was also the first project to develop European scenarios of sulfur and nitrogen dioxides that are consistent with the new global IPCC scenarios (the "SRES" scenarios) of greenhouse gases. The main significance of these long term emission scenarios is that they make it possible to compare the long term trends of regional air pollution with climate change in Europe. We believe the AIR-CLIM methodology is also applicable to other regions.

To compute the emission scenarios, further assumptions were made about the mitigation of emissions.

- The A1-P and B1-P scenarios assume that present air pollution policies are continued in Europe indefinitely, where "present policies" are defined as compliance with the so-called "Gothenburg Protocol" to the Convention on Long-Range Transboundary Pollution which specifies targets for 2010.

- The A1-A and B1-A scenarios assume "advanced" air pollution policies, that is, emission reductions increase over time up to a maximum value, and are achieved through end-of-pipe measures.
- The A1-550-P and A1-550-A scenarios add climate policies to the assumed air pollution policies. For these scenarios it is assumed that greenhouse gas emissions are reduced so that the atmospheric concentration of carbon dioxide stabilizes at 550 parts per million in the atmosphere over the long run (beyond the end of the 21st century) (In 2000 it was about 370 parts per million). This is a typical target discussed by researchers and climate policy advisors.
- The B1-450-P and B1-450-A scenarios include climate policies sufficient to stabilize carbon dioxide at 450 parts per million by 2100 which requires a lower level of carbon dioxide emissions than the "550 ppm" scenarios. The more stringent goal of these scenarios is justified because emissions are already lower in the B1 scenario because of lower fossil fuel use. This target is also commonly discussed.
- No reduction policies were assumed for ammonia emissions (which contribute to total nitrogen deposition). Nevertheless, these emissions vary over time (and between the A1 and B1 scenarios) because they are a function of the number of livestock and other indicators of agricultural activity which vary over time.

[Figure 2. SO_2 and NO_x emissions in Europe (left-hand side A1 scenarios, right-hand side B1 scenarios)]

The horizontal line in Figure 2 indicates the ceiling set on sulfur dioxide emissions by the Gothenburg Protocol mentioned above (as estimated in the AIR-CLIM Project). The scenarios of A1-P and B1-P "push up" against this line because fossil fuel use increases in these scenarios (due to economic growth) and this tends to increase sulfur dioxide emissions up to the Gothenburg ceiling. By contrast the climate policy scenarios (A1-550-P and B1-450-P) tend to reduce fossil fuel use in order to reduce carbon dioxide emissions and as a side-effect they also reduce emissions of sulfur dioxide. Hence, both the A1-P-550 and B1-450-P scenarios stay far below the Gothenburg ceiling (Figure 2). The same effect was computed for NO_x emission trends (Figure 2). These results can be interpreted to mean that climate policies make it "easier" for Europe to comply with the Gothenburg Protocol.

The remaining emission scenarios decrease over time, and even the scenarios mentioned above begin to decline after a few decades because of their declining use of fossil fuels. The only exception is the A1-P scenario for NO_x emissions which pushes up against the Gothenburg ceiling until the end of the century because of its relatively high fossil fuel use (Figure 2). We will see the consequences of these high NO_x emissions later when we examine the areas of Europe affected by nitrogen deposition.

After computing emissions we can then estimate the resulting deposition of acidity and nitrogen to the environment. To compute the deposition in Europe, the AIR-CLIM framework uses source-receptor matrices derived from the EMEP long range transport model of air pollutants in Europe. The matrices describe the deposition in different grid cells due to unit emissions from each country. They are averaged from 1985 through 1996 to minimize the effects of interannual meteorological variability. Since country-scale emissions are required for these calculations, the European sub-regional emissions calculated by IMAGE 2 (TIMER) are downscaled to the country-level using the distribution of emissions computed by the RAINS model.

Average deposition trends follow emission trends, and for the highest sulfur emission scenario (A1-P) sulfur deposition drops to below 0.7 g S m^{-2} a^{-1} in 2100 as compared to being above 10 g S m^{-2} a^{-1} in much of Central Europe through the 1980s. As noted above, most of the scenarios of NO_x emissions decline with time, but the highest scenario (A1-P) remains more or less constant. Since ammonia emissions (the other main contributor to nitrogen deposition) also do not change significantly, the level of nitrogen deposition hardly changes from current levels.

3.2 Long-term Scenarios of Greenhouse Gas Emissions and Climate Change

The rate of climate change in Europe depends not only on European greenhouse gases but on global emissions. These are computed in the AIR-CLIM framework by the TIMER submodel of IMAGE 2 (deVries et. al, 2000) for each of 17 world regions (including Western Europe, Eastern Europe, and the European part of the former USSR). The emission calculations are driven with assumptions about growth in population and the economy, and about technological development. These assumptions are consistent with the A1 and B1 storylines described above, and are used to compute the amount and type of energy combustion, the level of industrial and agricultural activity, and many other factors influencing emissions for the years 1990 to 2100. Emission factors for the different gases take into account regional differences in types of energy equipment and other regional factors.

Greenhouse gas emissions from Europe and elsewhere are summed up and input to the climate model in order to compute climate change. Computed are the atmospheric concentrations of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Also computed are regional concentrations of sulfate aerosol which have a cooling effect on the atmosphere as will be discussed shortly.

For all scenarios, the weighted sum of greenhouse gas emissions (the so-called "equivalent CO_2 emissions) peak around mid-century but the lag time of the climate system causes the global temperature to rise beyond the end of the 21st century. The average annual temperature change in Europe between 1990 and 2100 ranges from 1.2^0 to 1.8^0C for the B1 scenarios, and from 2.3^0C to 3.4^0C for the A1 scenarios. Meanwhile, annual average precipitation increases by more than a factor of two over the same period in parts of Northern Europe, but decreases up to 80 percent in parts of Southern Europe. Changes in precipitation over the rest of Europe lie between these extremes.

3.3 What is the Relative Importance of Regional Air Pollution and Climate Change in Europe?

3.3.1 Measures of Impact

Comparing the relative importance of regional air pollution and climate change in Europe requires a comparative measure of their impacts. For this purpose we use the concepts of "critical loads" and "critical climate". Critical loads are defined as "a quantitative estimate of an exposure to one or more pollutants below which significant harmful effects on specified sensitive elements of the environment do not occur according to present knowledge". Critical loads have been successfully used in negotiations about measures for reducing regional air pollution in Europe because they provide an aggregate measure of the impact of deposition on ecosystems. Two types of critical loads are used in AIR-CLIM, the critical load for acidity which is an estimate of the threshold of impacts for acid deposition (sulfur and nitrogen), and the critical load for eutrophication which is a measure of the threshold for the "over-fertilizing" effect of nitrogen deposition. It should be noted that critical loads are estimated only for forest soils because of their relevance to all European countries, and because of the difficulties in estimating critical loads for all soil types. In addition, it is thought that levels of deposition higher than critical loads pose a high risk of undesirable changes in forest and aquatic ecosystems. To compute critical loads we use the Simple Mass Balance (SMB) model and a standardized European data base of environmental data.

While critical loads have been used and accepted in Europe for several years, the concept of "critical climate" was newly developed in the AIR-CLIM Project with the aim of providing a more consistent basis for comparing the impacts of regional air pollution and climate change. The definition of critical climate is "quantitative values of a combination of temperature change and precipitation change which, if not exceeded, should avoid significant harmful effects on ecosystem functioning according to current knowledge". In AIR-CLIM, the critical climate thresholds were the combined changes in precipitation and surface temperature that lead to a decline of 10 percent or more in net primary productivity (compared to a base estimate). These thresholds were computed with the BIOME3 model, an advanced global vegetation model, using a standardized environmental database for Europe.

Since the concept of critical climate as defined above does not cover all types of climate impacts on vegetation we compute an additional indicator of climate impacts – the change in potential vegetation under climate change. Potential vegetation is the dominant vegetation type (or "biome") that occurs under particular soil and climate conditions. As climate changes, the potential vegetation at a particular location will also change, although the replacement of vegetation could take several decades or never occur at all. Hence a change in potential vegetation is a reasonable alternative indicator of the area affected by climate change.

We note that both the critical load and critical climate concepts cover only impacts on natural vegetation and do not take into account for example, impacts on human health, crop production, or the integrity of aquatic ecosystems (except that critical loads of forest soils are sometimes considered an indirect indicator of water acidification). On the other hand, risk to natural vegetation is an important impact category because damages to natural vegetation are especially difficult to mitigate, and because nature conservation is highly valued. For these and other reasons the critical loads concept is an accepted method for evaluating impacts on the European scale.

3.3.2 Areas Affected by Regional Air Pollution

We now use critical loads for acidity and eutrophication to evaluate the impact of regional air pollution on vegetation. In 1990 about 41 percent of Europe's area had acid deposition exceeding critical loads[1], including much of Central Europe and southern

[1] To estimate the area where critical loads of acidity and eutrophication are exceeded, we use the concept

Sweden. We noted above that most AIR-CLIM emission scenarios of sulfur dioxide and nitrogen dioxide show declining trends over the coming decades. This causes an overall decline in sulfur and nitrogen deposition, and by 2050 the area where acid deposition exceeds critical loads diminishes considerably (to 2.5 to 9.1 percent of Europe's area, depending on the emissions and deposition scenarios), and is very small by 2100 (0.7 to 4.7 percent). (See Figures 3 and 4).

By comparison, the area where nitrogen deposition exceeded critical loads of eutrophication was already larger than the area of acid deposition in 1990, ranging from northern and eastern France to the Baltic States. This area continues to be significant in 2050 (28.2 to 46.2 percent) and 2100 (14.6 to 37.0 percent) (Figures 3 and 4). The area is largest under the highest emissions scenario (A1-P) because emissions of NO_x and NH_3 remain fairly constant after 2010.

Summing up these points, while acidification as a problem is expected to diminish in Europe over the long run, the areas where critical loads of eutrophication are exceeded will continue to be significant.

[Figure 3. Areas where critical thresholds of regional air pollution and climate change are exceeded under the ***A1-P*** scenario. Top row: year 2050. Bottom row: year 2100. Left-hand side: regional air pollution. Middle: climate change. Right-hand side: overlapping areas. ("CLNut"= critical loads for nutrients (nitrogen deposition), "CLAci"= critical loads for acidity, "Biome change"= change in potential vegetation, "Crit.Clim."= critical climate)]

[Figure 4. Areas where critical thresholds of regional air pollution and climate change are exceeded under the ***B1-450*** scenario. Top row: year 2050. Bottom row: year 2100. Left-hand side: regional air pollution. Middle: climate change. Right-hand side: overlapping areas.
("CLNut"= critical loads for nutrients (nitrogen deposition), "CLAci"= critical loads for acidity, "Biome change"= change in potential vegetation, "Crit.Clim."= critical climate)]

3.3.3 Areas Affected by Climate Change

For climate change, the estimates of the affected area varies greatly depending on the chosen indicator (either the area where climate change exceeds the critical climate, or the area with changed potential vegetation). For the highest and lowest emission scenarios, the area where the change in temperature and precipitation exceeds the critical climate threshold ranges from 7.6 to 11.0 percent of Europe's area in 2050, and increases to 10.0 to 12.6 percent in 2100. The areas affected are among those with marginal vegetation and extreme and variable climate, including most of the Iberian Peninsula, parts of France and Greece and a section of the Alps (Figures 3 and 4).

Meanwhile, the areas with changed potential vegetation are much larger, ranging from 30.1 to 46.0 in 2050 and 36.6 to 64.2 percent in 2100, and cover much of Northern and Eastern Europe (Figures 3 and 4). These calculations can be interpreted to mean that a small part of Europe might experience a significant drop in the *productivity* of its vegeta-

---

of "average accumulated exceedances" which takes into account the contribution of both sulfur and nitrogen deposition to the acid load to the environment.

tion (as indicated by the exceedance of critical climate thresholds) whereas a much larger part may experience a change in the *type* of vegetation.

3.3.4 Areas Affected by Both Regional Air Pollution and Climate Change

While the areas affected by regional air pollution decline over the coming decades (rapidly for acidity and slowly for eutrophication), the areas affected by climate change expand because of the cumulative effects of climate change. Given these opposing trends, around the middle of the century both problems could be significant in Europe at the same time. How much area will be affected in total by one or the other problem? Will there be areas of overlap?

We estimate that in the year 2050 practically all of Europe's area will be affected by either (or both) regional air pollution and climate change, as defined above (Figures 3 and 4). The areas of overlapping impacts cover about 16 to 31 percent of Europe's area (depending on the scenario) and included parts of all European sub-regions from Portugal to the Ukraine, and from Greece to Sweden. (Figures 3 and 4). The indicators affected in most of these overlapping areas are critical loads for nitrogen deposition and changed potential vegetation because of climate change. However, for the highest emission scenario, parts of Spain and France will have unfavorable values for all indicators of impacts of regional air pollution and climate change, indicating that natural vegetation in these areas may be particularly at risk (Figure 3).

3.4 What are the Linkages between Regional Air Pollution and Climate Change in Europe's Environment?

3.4.1 Will Climate Change Affect the Distribution of Regional Air Pollution in Europe?

Changes in climate will be manifested in many ways, including changes in annual and seasonal wind and precipitation patterns in Europe. These changes will, in turn, alter the pattern of acid deposition and nitrogen deposition in Europe. This is important from the policy standpoint because existing agreements to control emissions are based on reducing deposition under current climate conditions. The question arises, will climate change have a significant effect on the basic source-receptor relationships in Europe? To address this question we have compared the deposition calculated with the EMEP model of long range transport in Europe under current and future climate conditions. These model experiments were carried out under the framework of AIR-CLIM. The data on future climate conditions were produced by a "higher" resolution (1.1^0) climate model for Europe ("ECHAM/OPYC") which simulated European climate of the 2040s assuming a medium reference scenario of greenhouse gas emissions (the "IS95a" scenario which is an update of the standard "IS92a" scenario of the Intergovernmental Panel on Climate Change without sulfur). These data were input to the EMEP model and compared to a control case using model climate data for the 1970s. Emissions of sulfur dioxide, nitrogen oxides, and ammonia were set constant at their 1996 levels. Since all factors other than meteorology were held constant, the difference in deposition between the 1970s and 2040s were only due to the change in climate simulated by the climate model.

It was found that deposition of sulfur and nitrogen was on the average lower in the 2040s than the control period because of slightly increased export of emissions from Europe. The cause of this export may be related to the effect of changed climate on the dry deposition processes simulated by the EMEP model.

The largest decreases computed for sulfur and nitrogen deposition were about 12 percent (country average). The largest increases in sulfur deposition were about 5 percent, and for oxidized nitrogen about 2 percent. In general these model experiments showed only a relatively small influence of climate change on the distribution of acid deposition and nitrogen deposition in Europe.

We must emphasize that these are only the first results of model experiments linking the output of climate change models with the input of long range transport models of air pollution in Europe. Moreover, only one one climate scenario was investigated, and only the deposition of sulfur and nitrogen was studied. Hence results should be taken as very preliminary.

3.4.2 Will Climate Change Affect the Sensitivity of European Ecosystems to Regional Air Pollution?

3.4.2.1 Impact of Climate Change on Critical Loads

The critical loads used in AIR-CLIM can be interpreted as a measure of the sensitivity of forest ecosystems to acid deposition and nitrogen deposition. Ecosystems are more sensitive to deposition when the critical loads are lower, and less sensitive when they are higher. Will a change in average climate alter critical loads? Theoretically, yes, because the biochemistry that determines the resilience of forest soils to deposition depends on precipitation, temperature and net primary productivity (which is also a function of climate). As these variables change, we expect the resilience of forest soils to change. We can compute this effect with the model used to compute critical loads. Using this model, together with the typical changes in temperature, precipitation, and net primary productivity that occur under the AIR-CLIM climate scenarios discussed above, we estimate that the change in critical loads at a particular location should not exceed 10 to 15 percent. As temperature increases, the average weathering rate of soils also increases, and this provides additional chemicals to neutralize acid deposition. For this and other reasons, forest soils, on average, will have higher critical loads. Put another way, forest soils under climate change may become less sensitive to acid deposition. However, some parts of western coastal regions and in mountainous regions will become more sensitive. For nitrogen deposition, forest soils almost everywhere become less sensitive except in the Alps and the western Iberian Peninsula.

We must emphasize that the concept of critical loads cannot accurately take into account all possible impacts of climate change on the sensitivity of ecosystems to regional air pollution. For example, the computation of critical loads does not take into account changes in the seasonality of precipitation and temperature which could also affect the resilience of forest soils. Hence, the conclusions presented here must be taken as very preliminary.

3.4.2.2 Comparing the Impact of Climate Change on Deposition and Critical Loads

Above we have seen that climate change can alter the meteorological factors that influence critical loads, and as a result, can change the extent of area in which critical loads are exceeded. But climate change also modifies the deposition patterns in Europe and in this way also changes the areas of exceedance of critical loads. Which effect is more important? Table 1 summarizes results from a sensitivity analysis. The basic finding is that the effect of climate change on deposition is quite small compared to its effect on critical loads. For example, under present climate conditions, the area where critical loads of nitrogen are exceeded ranges from only 55.6 to 58.1 percent because of the influence of climate change on deposition patterns, but varies from 46.2 to 58.1 percent because of its influence on critical loads.

[Table 1. Sensitivity analysis of the percentage of European forest area for which critical loads for acidity and eutrophication are exceeded in 2050 under the A1-P scenario.]

3.4.2.3 Impact of Climate Change on Critical Levels

Up to now we have used critical loads as a tool to evaluate the impact of emissions, via deposition, on forest ecosystems. We now use a parallel concept, "critical levels" to examine the impact of emissions on natural vegetation via air concentrations. Critical levels are estimates of the air concentration of sulfur dioxide, nitrogen oxides and other substances below which no harm is expected to plant productivity. In the AIR-CLIM Project we have estimated the impact of climate change on these critical levels by recomputing the "stomatal conductance" of typical European trees (a measure of the flux of substances between the tree and its environment) under future climate conditions and comparing it to current climate conditions.

In general, it was found that climate change increases the sensitivity of plants to specified levels of air pollutants in the boreal forests of Northern Europe, while it decreases plant sensitivity in temperate areas. Plants become more sensitive because of the warmer temperatures brought on by climate change which boosts the water stress experienced by vegetation. But according to the AIR-CLIM climate scenarios, temperature increases are accompanied for many decades by increasing carbon dioxide concentrations, and carbon dioxide tends to counteract the impact of temperature. The tradeoff of the temperature and carbon dioxide effects leads to the surprising result that plant sensitivity to air pollution reacts more strongly to climate change in the first half of the century than in the second half.

But overshadowing the conclusions about sensitivity, are the findings that air concentrations of sulfur dioxide and nitrogen oxides are, and will continue to be, far below "critical levels" in most rural parts of Europe. This implies that these substances pose a low risk to forest ecosystems. We note however, that these calculations have only been carried out for sulfur dioxide and nitrogen oxides, and results may be different for ozone which periodically reaches high levels in Europe.

3.4.3 What will be the Impact of Regional Air Pollution on Climate Change in Europe?

For some time scientists have established a link between sulfate aerosol in the atmosphere (stemming partly from sulfur dioxide emissions) and climate. It turns out that sulfate aerosol reflects a significant portion of the sun's heat radiation, and in this way tends to cool the lower atmosphere, and compensate somewhat for the warming caused by greenhouse gases. How important is this effect in Europe? As part of AIR-CLIM, we conducted experiments with the climate submodel of the IMAGE 2 model which takes into account the above-mentioned effect of sulfate aerosol. Other potential warming or cooling effects of sulfate on the atmosphere, such as its influence on cloud cover/depth and the occurrence of precipitation, are not taken into account by the model. Two AIR-CLIM scenarios (A1-P and B1-450-A) were run with a reasonably wide range of high and low sulfur dioxide emissions, to investigate the impact of these emissions on climate. The main finding was that a wide range of SO_2 emissions causes only a small difference in temperature (0.1^0C to 0.2^0C, European annual average). Hence, for these model experiments, the influence of sulfate in the atmosphere on Europe's temperature is rather small. These results must be qualified, however, by noting that larger differences in temperature occur at some locations. Moreover, experiments with different emission scenarios and models could give different results.

3.5 What will be the Impact of Climate Policies on the Costs of Controlling Regional Air Pollution?

Not only does climate change affect deposition, critical loads and critical levels, but it also has an effect on the costs of regional air pollution. This is logical since fossil fuel use is a common and major source of both greenhouse gas emissions and air pollution emissions. To analyze this effect we first return to the assumptions of the AIR-CLIM climate policy scenarios. These policies aim to reduce CO_2 emissions so that average CO_2 in the atmosphere is stabilized at 450 ppm and 550 ppm (compared to approximately 370 ppm in year 2000). To achieve these targets, it is assumed that a world-wide tax on the carbon content of fuels is imposed on energy users. This so-called "carbon tax" stimulates a variety of actions. For example:

- investments and implementation of energy efficiency,
- the substitution of high carbon fuels with lower carbon fuels (for example coal with natural gas),
- higher levels of world trade in lower carbon fuels, and
- investments and construction of low or non-carbon alternatives such as wind energy, solar energy, biofuels, and nuclear energy.

These actions tend to bring down the overall carbon content of fuels in the economy which in turn reduces CO_2 emissions. But the main point here is that reducing the carbon content of fuels also tends to reduce the emissions of sulfur and nitrogen oxides. Hence a side benefit of controlling CO_2 emissions is the collateral reduction of air pollution emissions, and potential cost savings in reducing these emissions. Estimating these side benefits of reducing greenhouse gases is not new, but it has not yet been carried out for a set of scenarios as comprehensive as in the AIR-CLIM Project.

To estimate these cost savings we first use sub-regional cost curves to estimate the costs of reducing sulfur dioxide and nitrogen dioxide emissions. These curves specify the marginal costs of, and technical potential for reducing sulfur dioxide and nitrogen dioxide emissions in different European sub-regions. Only "add-on" measures are taken into account. Hence, these curves imply that emissions may be reduced only by add-on measures over the long run, and this may not be a realistic assumption, as discussed shortly.

For the A1 scenarios (with higher economic growth and fossil fuel use than the B1 scenarios) the annual costs of reducing sulfur dioxide emissions (without climate policies in place) are estimated to be between 0.19 and 0.31 percent of Europe's GDP in 1995 (depending on the reduction level).[2] These are the long-term (2000 to 2100) average costs. (We present cost data as a percentage of the European GDP in 1995 to provide a common basis for comparing scenarios.) But if climate policies are in place, then the costs of add-on technologies to control SO_2 could be reduced by about 70 percent because of decreased fossil fuel use. Cost savings are lower (around 55 percent) for the B1 scenarios, because base emissions are already much lower than under the A1 scenarios again because of lower fossil fuel use.

For NO_x emissions, the long term average annual costs for emission reductions (without climate policies) are somewhat higher than for sulfur dioxide, being about 0.51 to 0.75 percent of European GDP in 1995. But climate policies would also lower the baseline NO_x emissions and thereby save a substantial sum for add-on measures. The cost savings with climate policies in place are estimated to be 40 to 55 percent, as compared to scenarios without climate policies.

These calculations assume that air pollution policies focus only on "add-on" measures to reduce emissions such as flue gas desulfurization or desulfurizing fuels, rather than on strategies to reduce energy use or switch to new fuels. But the reality is that switching fuels and reducing energy use are already part of policies to reduce SO_2 and NO_x emissions in Europe (and elsewhere), and will be even more important over the long run. This implies that the above cost savings are probably overestimated. But this does not take away from the significance of the above results; it only suggests a different conclusion, namely that costs of controlling environmental pollution can be substantially reduced by developing "joint strategies" for reducing both CO_2 emissions and air pollution emissions.

3.6 Uncertainties, Gaps in Knowledge, Need for Research

3.6.1 Integrated Assessment of Other Substances

While the above conclusions hold for sulfur and nitrogen as regional pollutants, they will not necessarily hold for other important regional pollutants such as persistent organic pollutants and oxidants. These other pollutants do not have the same chemical characteristics as sulfur and nitrogen, and therefore respond differently to wind, temperature, precipitation and other aspects of climate. Hence, an assessment of the connection between

[2] These costs will not be as high a percentage of GDP in the future because GDP grows by a factor of 6 in Western Europe and 40 in Eastern Europe and Russia under the A1 scenario.

these substances and climate change would be interesting from both the scientific and policy perspective.

3.6.2 Comprehensive but not Definitive

The AIR-CLIM Project was comprehensive but not definitive. While it was comprehensive geographically, and in its coverage of economic, emissions, atmospheric and ecological aspects of air pollution and climate change, it was nevertheless limited in scope.

- Future research should focus not only on impacts to natural vegetation, but also on impacts to human health, crop production, and aquatic ecosystems, among other categories.
- Cost calculations should investigate not only the side benefits of climate policies to reductions of air pollution emissions, but should evaluate truly *joint policies* having the objective to simultaneously reduce greenhouse gas and air pollution emissions.
- In order to include climate change in any analysis it is necessary to use climate scenarios. These scenarios have large uncertainty because they are generated by models that must make a large number of approximations to simulate global atmospheric processes. This uncertainty can be somewhat reduced by using output from the new generation of regional climate models that can better simulate finer scale meterological processes important in Europe.

4 SCIENTIFIC INTEREST AND NOVELTY

4.1 Development of New Information/Data

Development of detailed emission scenarios. AIR-CLIM was the first study to work out consistent, detailed emission scenarios of gases that lead to both regional air pollution (sulfur dioxides and nitrogen oxides) and the new IPCC global scenarios of greenhouse gases.

Significance: This provides a method for other researchers (in Europe and elsewhere) to carry out regional studies of air pollution and climate change. For Europe, it allows a comparison of future trends in regional air pollution and climate change in a consistent manner.

Development of long-term scenarios of air pollution emissions. Virtually all available scenarios of air pollution emissions are short to medium term (up to a few decades), with the main exception being regional sulfur dioxide emissions (because of their importance to climate change). The AIR-CLIM Project produced long term (up to 2100) scenarios of sulfur dioxide, nitrogen oxides, and ammonia emissions.

Significance: These data can serve as a useful input to long term prognostic studies of environmental change in Europe.

Development of long-term scenarios of deposition and air concentration. The AIR-CLIM combined the long-term emission scenarios mentioned above with a source-receptor matrix and generated very unique scenarios of long term deposition and air concentrations in Europe.

Significance: These long-term scenarios can serve as direct input into research projects (or models) about long-term cumulative impacts of regional air pollution in Europe.

4.2 Development of New Methods

Development of the critical climate concept. While critical loads have been used and accepted in Europe for several years, the concept of "critical climate" was newly developed in the AIR-CLIM Project with the aim of providing a more consistent basis for comparing the impacts of regional air pollution and climate change.

Significance: The concept of critical climate can be a useful new tool for researchers in their assessments and analyses of climate impacts on natural vegetation.

The simultaneous usage of critical loads, critical levels, and critical climate in AIR-CLIM. The AIR-CLIM Project pioneered the use of "critical thresholds" to allow a consistent comparison of impacts on natural vegetation due to deposition, air concentration, and climate change.

Significance: This methodology can be applied to many other regional and sub-regional assessments.

The AIR-CLIM Approach. A methodology was developed in the AIR-CLIM Project that may be relevant to other researchers. Components of existing integrated models were coupled and supplemented with new components.

Significance: This approach made it possible to build a complex modeling framework in a short period of time and made more time available for scenario analysis and conducting model experiments.

4.3 New Scientific Findings

The overlap areas of regional air pollution and climate change may be considerable in 2050

Significance: These results could signal the locations of particular environmental stress in the future. Scientists should consider long term monitoring of these areas.

The impact of climate change on ecosystem sensitivity may not be significant. With scenario analysis and model experiments the AIR-CLIM Project found that a change in climate led to a small change in critical loads and critical levels.

Significance: An interesting question for researchers is whether these findings can be confirmed or contradicted by field studies.

The impact of climate change on the long range transport and deposition of sulfur and nitrogen in Europe may not be significant. For the first time, the detailed output from a climate model was used as input to a long range transport model of pollutants. But the difference in deposition between current and future climate conditions was not found to be great.

Significance: One interesting scientific question is whether this conclusion can hold up to other model experiments, other climate scenarios, and the use of other climate models and long range transport models. Another interesting scientific question is whether climate change will have the same or different impact on ozone and other important pollutants in Europe.

5 POLICY RELEVANCE

Some AIR-CLIM results have particular policy-relevance:

Europe's forests may be subjected to a continuing risk of eutrophication. Over the next few decades the area affected by acidification will diminish, but the areas affected by eutrophication (over-fertilization of forest soils by nitrogen deposition) will remain large.

Significance: Present and even accelerated policies to control NO_X emissions may be inadequate in providing long-term protection to Europe's forest ecosystems from the effects of nitrogen deposition. In light of this, policies for reducing NO_x and NH_3 emissions need to be closely examined.

Climate policies make it "easier" for Europe to comply with the Gothenburg Protocol. Climate policies usually aim to reduce fossil fuel use in order to reduce carbon dioxide emissions. As a side effect they also reduce emissions of sulfur dioxide and nitrogen dioxides. In the AIR-CLIM Project this effect was found to be very significant.

Significance: The Gothenburg Protocol puts a "ceiling" on emissions, and climate policies that aim to reduce greenhouse gas emissions may, as a side benefit, help countries stay below the Gothenburg ceiling.

Climate policies can lead to large cost savings in reducing air pollution emissions. As just noted, climate policies are expected to lead to lower fossil fuel use, and this will lead to lower baseline emissions for air pollution emissions. This implies that the costs of "add-on" measures will be cheaper because they start from a lower baseline of emissions.

Significance: If climate policies inadvertently lead to reductions of air pollution emissions, as explained above, then it can be argued that these are "bonus", no-cost reductions.

Climate change may not have a large effect on critical loads and levels. According to the scenarios developed in AIR-CLIM there should not be a large change in the sensitivity of forest ecosystems to air pollution.

Significance: It does not seem that the effects of climate change will change the effectiveness of current international agreements to reduce air pollution emissions. However, critical loads do not necessarily represent all of the possible impacts of climate change on ecosystem sensitivity. Therefore this question must be studied more carefully.

Climate change may not have a large effect on the transport and deposition of sulfur and nitrogen in Europe's atmosphere. According to preliminary model experiments, future climate conditions did not substantially change the distribution of emissions and deposition in Europe.

Significance: As in the preceding point, climate change may not change the assumptions about source-receptor relationships built into current international agreements. However, the same qualifications apply to this conclusion as to the preceding conclusion.

Summing Up

Some main points are:

Regional air pollution and climate change may be fairly weakly coupled in the natural environment –

- Climate change was not found to have a large impact on the sensitivity of forest ecosystems, nor on the distribution of deposition.
- Regional air pollution (in the form of sulfate aerosols) was not found to have a large effect on climate change in Europe.

But regional air pollution and climate change may be strongly coupled in the policy environment –

- An important observation is that virtually all of Europe at mid-century might be affected by either regional air pollution or climate change, or both. This will require a strong policy response since virtually all European citizens may be living near impacted areas.
- Regional air pollution and climate change were also found to have close potential links in cost policies – As noted above, climate policies can bring large indirect cost savings for reductions of air pollution emissions. There are strong financial arguments for developing *joint* policies to reduce air pollution and greenhouse gas emissions in Europe.

6 COLLABORATION

6.1 Collaboration with other EU research projects

The Kassel group is in close contact with the team at International Institute of Applied Systems Analysis (IIASA) in Laxenburg, Austria, that developed and analyzed cost-effective approaches to control European air quality with the RAINS model as part of a contract with the European Commission (DGXI) (Study Contract B4-3040/97/000654/MAR/B1).

Joseph Alcamo of the Kassel Group is a member of the Steering Committee of the European Forum on Integrated Environmental Assessment (EFIEA), which is an EC-Concerted Action. The objective of the EFIEA is to develop European standards of practice of integrated environmental assessments, and to broaden the usage of these assessments.

6.2 Other

The Kassel group participated in the ICLIPS project (Integrated Assessment of Climate Protection Strategies) for the German Ministries of Research and Education and for Environment (Bundesministerium für Bildung und Forschung (BMBF) und Bundesministerium für Umwelt (BMU)). The main objective of ICLIPS was to develop a modeling framework that can be used to examine strategies for climate change mitigation. Concepts developed under the auspices of ICLIPS are also partly applicable to the AIR-CLIM project.

The Kassel group participates in the project 'New methodologies to analyze interactions of climate change, acidification and ozone' for the Dutch NOP. Project leader is E.C. van Ierland from Wageningen Agricultural University (WAU-WIMEK). The Kassel group contributes to the development of emission scenarios and to atmospheric transport calculations under climate change.

Joseph Alcamo from the Kassel group and the IMAGE team at RIVM were closely involved in the 'Special Report on Emission Scenarios' for the IPCC. Joseph Alcamo and Bert de Vries are lead authors of the report while the IMAGE team is responsible for one of the new standard scenarios. Joseph Alcamo is also a lead author of the assessment of mitigation scenarios being carried out under the Third Assessment of IPCC.

Maximilian Posch from the Bilthoven group collaborates with ALTERRA Green World Research (Wageningen University Research) in updating and improving the pan-European forest-soil map, which forms the basis for the critical load calculations.

7 LIST OF PUBLICATIONS

7.1 Submitted

J. Alcamo, P. Mayerhofer, M. Posch, J.G. van Minnen, R. Guardans, B. de Vries, T. van Harmeln, J. Onigkeit, D. van Vuuren, M. den Elzen, J. Bakker, (2001) “The linkage between regional air pollution and climate change in Europe: an overview of the assessment's results”, Environmental Science and Policy (submitted).

R. Guardans, (2001) “The influence of climate change on the sensitivity of European vegetation to air pollutant concentrations”, Environmental Science and Policy (submitted).

P. Mayerhofer, R. Guardans, M. Posch (2001) “The effects of climate change on transport of acidifying pollutants and on exceedances of their critical thresholds in Europe”, Proceedings of IUAPPA 2001, Atmospheric Environment (submitted)

P. Mayerhofer, B. de Vries, M. den Elzen, D. van Vuuren, J. Onigkeit, M. Posch, (2001) “Integrated scenarios of emissions, climate change and regional air pollution in Europe”, Environmental Science and Policy (submitted).

M. Posch (2001) “The linkage between climate change, regional air pollution and critical deposition and loads in Europe”, Environmental Science and Policy (submitted).

T. van Harmelen, J. Bakker, B. de Vries, D. van Vuuren, M. den Elzen, P. Mayerhofer (2001) “An analysis of the economic costs and savings of joint reduction policies to mitigate climate change and air pollution in Europe”, Environmental Science and Policy (submitted).

J. G. van Minnen, J. Onigkeit, J. Alcamo, (2001) “The development and application of a critical climate concept for Europe”, Environmental Science and Policy (submitted).

7.2 In Press

P. Mayerhofer, J. Alcamo, M. Posch, J. G. van Minnen (2001) Regional air pollution and climate change in europe: An integrated assessment (AIR-CLIM). Water, Air and Soil Pollution (in press)

7.3 Technical Reports

P. Mayerhofer, J. Alcamo, J. G. van Minnen, M. Posch, J.-P. Hettelingh, R. Guardans, B. S. Gimeno (1999) *Regional Air Pollution and Climate Change in Europe: An Integrated Analysis (AIR-CLIM) - Progress Report 1*. WZ Report A9901, Center for Environmental Systems Research, Kassel.

P. Mayerhofer, J. Alcamo, J. G. van Minnen, M. Posch, R. Guardans, B. S. Gimeno, T. van Harmelen, J. Bakker (2000) *Regional Air Pollution and Climate Change in Europe: An Integrated Analysis (AIR-CLIM) - Progress Report 2*. WZ Report A0001, Center for Environmental Systems Research, Kassel.

P. Mayerhofer (2001) *An analysis of impacts of climate change on regional acidifying pollution*. WZ Report A0101, Center for Environmental Systems Research, University of Kassel, Kassel.

J. Onigkeit (2001) *An inventory of uncertainties of the AIR-CLIM modeling framework*. WZ Report A0103, Center for Environmental Systems Research, University of Kassel, Kassel

7.4 Presentations:

J. Alcamo, P. Mayerhofer, J. G. van Minnen, M. Posch, B. de Vries, T. van Harmelen, R. Guardans, J. Onigkeit, M. den Elzen, D. van Vuuren, J. Bakker (2001) The linkage between regional air pollution and climate change in Europe: results of an integrated assessment. Presentation at *Challenges of a Changing Earth* – Global Change Open Science Conference 10-13 July, 2001, Amsterdam, The Netherlands.

M. Posch, J.-P. Hettelingh, P. Mayerhofer (2001) Past and future exceedances of nitrogen critical loads in Europe. Presentation at Second Nitrogen Conference

J. G. van Minnen, J. Onigkeit, J. Alcamo, M. Posch (2001) Critical climate: An indicator to assess climate change risks in Europe. Presentation at *Challenges of a Changing Earth* – Global Change Open Science Conference 10-13 July, 2001, Amsterdam, The Netherlands

8 OTHER INFORMATION ACTIVITIES

The website of the AIR-CLIM project can be found at:
http://www.usf.uni-kassel.de/air-clim

References

Alcamo, J., G. J. J. Kreileman, M. Krol *et al.* (1998) "Global modeling of environmental change: an overview of IMAGE 2.1", pp. 3-94 in J. Alcamo, R. Leemans, G. J. J. Kreileman (Eds.) *Global change scenarios of the 21st century. Results from the IMAGE 2.1 model*. Pergamon Press.

Alcamo, J., Shaw, R., Hordijk, L. (eds.) (1990) *The RAINS model of acidification: Science and strategies in Europe*. Kluwer Acad. Publ., Dordrecht.

Amann, M., Baldi, M, Heyes, C., Klimont, Z., Schöpp, W. (1995) „Integrated assessment of emission control scenarios including the impact of tropospheric ozone", *Water, Air, and Soil Pollution* 85: 2595-2600, Kluwer Acad. Publ., Dordrecht.

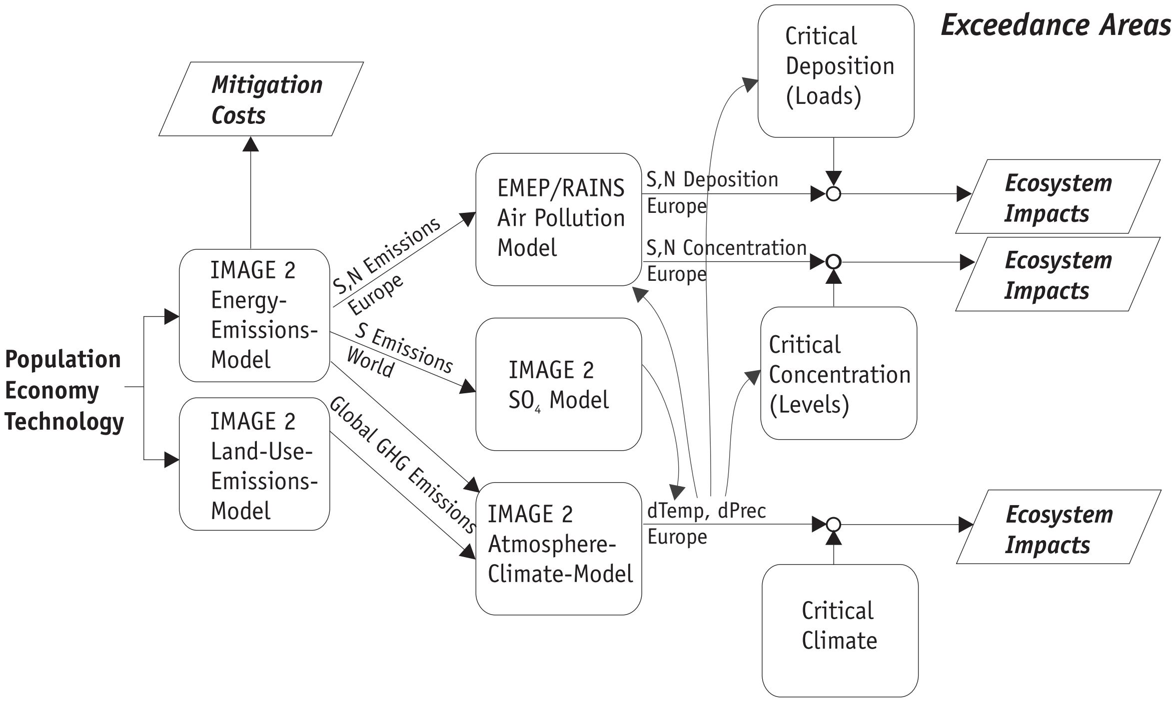

Figure 1 The integrated modeling framework of AIR-CLIM.

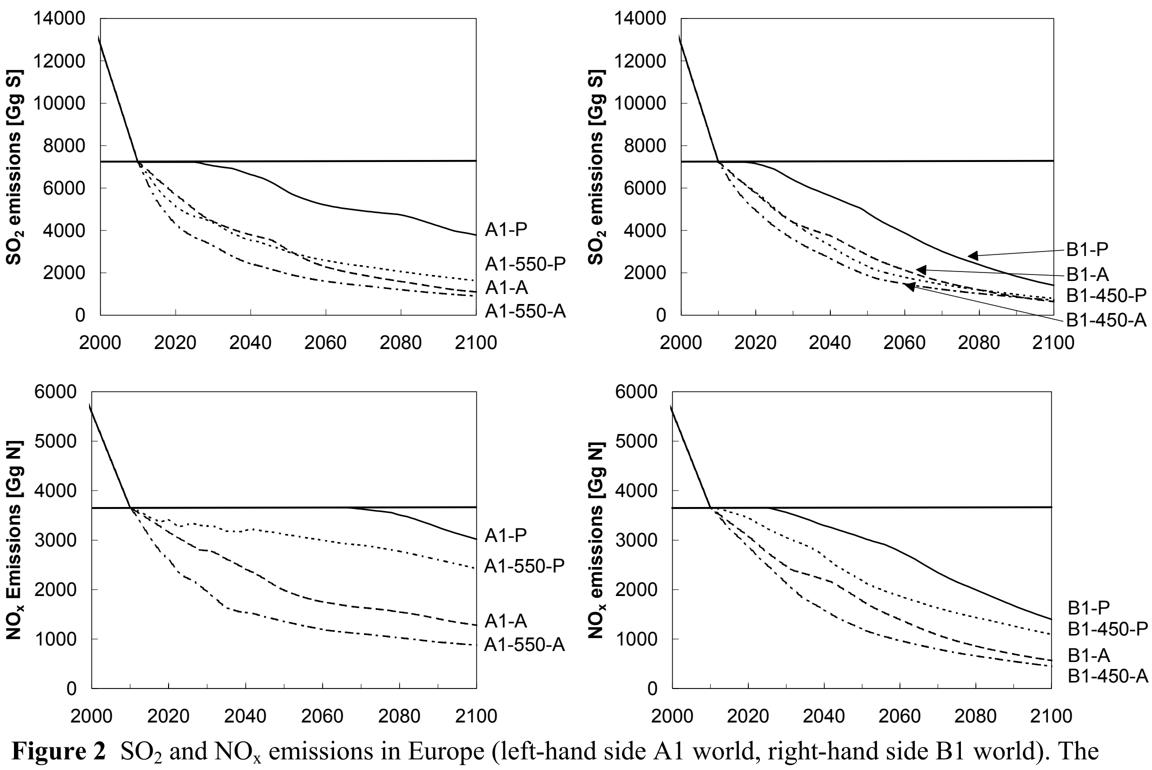

Figure 2 SO_2 and NO_x emissions in Europe (left-hand side A1 world, right-hand side B1 world). The horizontal line represents the Gothenburg level of emissions.

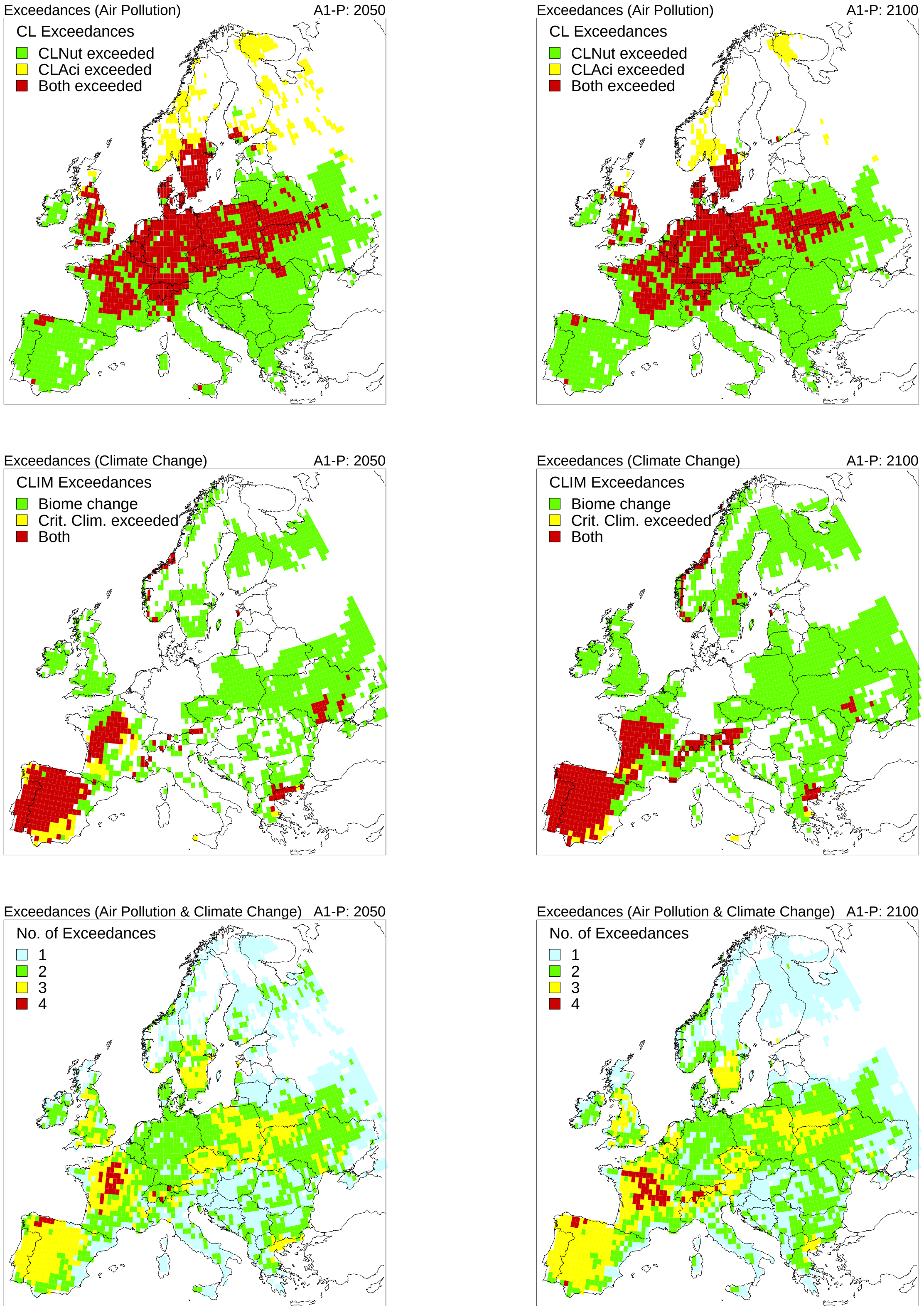

Figure 3 Areas where critical thresholds of regional air pollution and climate change are exceeded under the ***A1-P* scenario**. Left-hand side: year 2050. Right-hand side: year 2100. Top row: regional air pollution. Middle: climate change. Bottom row: overlapping areas. *("CLNut"= critical loads for nutrients (nitrogen deposition), "CLAci"= critical loads for acidity, "Biome change"= change in potential vegetation, "Crit.Clim."= critical climate).*

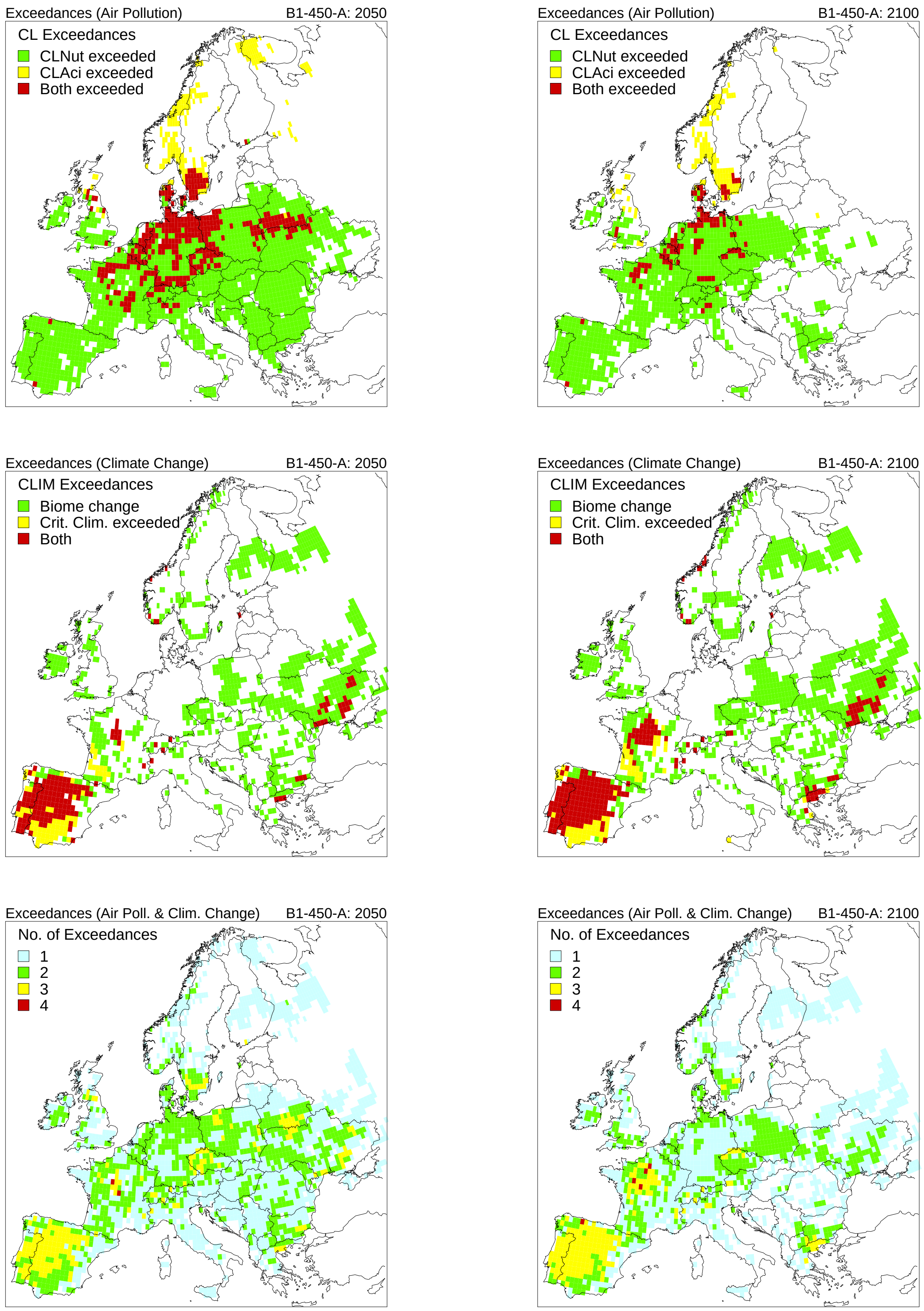

Figure 4. Areas where critical thresholds of regional air pollution and climate change are exceeded under the ***B1-450-A* scenario**. Left-hand side: year 2050. Right-hand side: year 2100. Top row: regional air pollution. Middle: climate change. Bottom row: overlapping areas. *("CLNut"= critical loads for nutrients (nitrogen deposition), "CLAci"= critical loads for acidity, "Biome change"= change in potential vegetation, "Crit.Clim."= critical climate).*

Table 1 Percentage of European forest area for which acidity and nutrient N critical loads (CLs) are exceeded in 2050 under the A1-P scenario, taking into account climate change in critical load and/or deposition calculations.

Deposition calculated with	Acidity CLs calculated with		Nutrient N CLs calculated with	
	present climate	changed climate	present climate	changed climate
present climate	15.4%	**9.1%**	58.1%	**46.2%**
changed climate	14.3%	8.2%	55.6%	44.0%