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Sulphur and nitrogen oxides emissions in Europe and deposition in Finland during the 21st century

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This paper describes the development of European scenarios of sulphur and nitrogen oxide emissions and resulting depositions in Finland during the 21st century, based on the IPCC Special Report on Emissions Scenarios. The work is a part of the FINSKEN project, which aimed at developing consistent long-term scenarios of global change for Finland. The derivation of emission scenarios for European countries and the calculation of environmental loading scenarios based on them presented in this paper is analogous to the estimation of future ground level ozone concentrations within FINSKEN. Global energy scenarios are reflected in changing emission quantities in Europe. Deposition scenarios up to the year 2100 are developed using European and regional deposition models. The impacts of alternative energy futures on emissions and regional air pollution are compared with the plausible impacts of climate change on the transformation and transportation of air pollution, based on the work in the European AIR-CLIM project. The long-term emission scenarios are developed taking into account the recent international emission reduction agreements within the UN/ECE and the EU. Comparisons between IPCC scenarios and European developments indicated that the fossil-intensive IPCC scenarios were pessimistic in their estimates for future sulphur and nitrogen oxides emissions for European regions. In the light of recent air pollution reduction legislation in Europe, increasing sulphur and nitrogen oxides deposition trends for Finland appear unlikely.

Introduction

Transboundary air pollution with its adverse environmental impacts has been a severe environmental problem in Europe and North America for decades. Acidification damages to water and forest ecosystems caused mainly by long-range transported air pollution have been widespread, affecting seriously not only the most polluted areas but also the sensitive background regions of the Nordic countries (e.g. Rask *et al.* 1995, Henriksen *et al.* 1998, Lorentz *et al.* 2000). Forest ecosystems have been shown to have long recovery times of acidification even when deposition loads are effectively cut (e.g. Ahonen *et al.* 1998).

Eutrophication of soils caused by excess nitrogen deposition is estimated to affect presently about 55% of the European ecosystem area (Amann *et al.* 1999), enhancing ecosystem productivity, but also causing adverse effects such as overfertilisation, nitrate leaching and

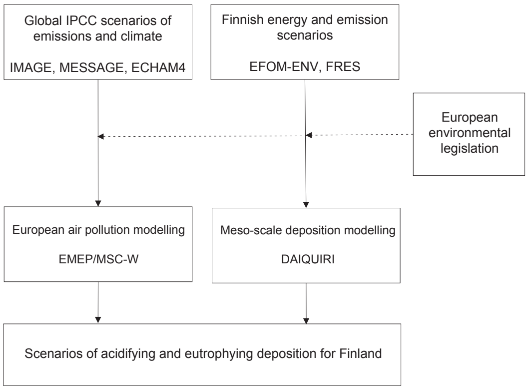

Fig. 1. The modelling framework, models and data used in the study.

changes in species occurrence. Eutrophication of the Baltic Sea with regularly occurring toxic cyanobacteria blooms is presently among the most serious environmental problems in the Nordic countries (Kiirikki *et al.* 2001). Due to the increased control of direct nitrogen discharges (industry, households and agricultural leaching) to the Baltic Sea, the contribution of nitrogen originating from atmospheric deposition receives growing attention. The impacts of atmospheric nitrogen deposition are aggravated by the fact that, being mainly in inorganic form, it is readily available for algae production.

Regional air pollution issues and climate change are closely interlinked in several ways. Climate change is known to cause changes in the ecosystem tolerance against air pollution (IPCC 2001a, Alcamo *et al.* 2002, Posch 2002), including the impacts of climate change on sea eutrophication (e.g. Inkala *et al.* 1997). Climate change also affects the transformation and transportation of pollutants in the air (Mayerhofer *et al.* 2002). Mitigation measures of climate change are known to affect the emissions of many important air pollutants (e.g. Cifuentes *et al.* 2001, Metz *et al.* 2001, Syri *et al.* 2001). If realised, the mitigation of climate change will undoubtedly be a major driver also in regional air pollution issues in the coming decades. The side-impacts of climate change mitigation measures were also recognised by the Intergovernmental Panel on Climate Change (IPCC) as an important research priority in its recent Synthesis Report (IPCC 2001b). In addition, regional air pollutants are important greenhouse agents. Especially sulphate aerosols in the atmosphere cause significant negative forcing on the regional radiation balance.

This paper analyses the implications of plausible future global and regional energy and emissions developments for regional air pollution, focusing on Finland. This work is a part of the FINSKEN project, which aimed at developing consistent long-term scenarios of global change and its impacts for Finland, including climate change, air pollution, sea level rise and socio-economic changes. In this study, global and regional medium- and long-term energy use scenarios are combined with national projections to assess the future perspectives of acidifying and eutrophying deposition. Deposition scenarios for Finland up to the year 2100 are developed, considering both the changes in emissions levels caused by the alternative energy futures and the plausible impacts of climate change on the transportation and transformation of air pollutants. The global scenarios are used together with existing more detailed regional modelling and projections, considering also the recent European emission reduction agreements within the United Nations Economic Commission on Europe (UN/ECE) and the EU. Corresponding analysis concerning long-term scenarios of tropospheric ozone in Europe has been carried out at the Finnish Meteorological Institute (Tuovinen *et al.* 2002, Laurila *et al.* 2004).

Methods

The analysis was done by linking the results of integrated assessment models of global change with existing long-range and meso-scale models of air pollution. National-scale energy and emissions projections were used together with coarser global and regional scenarios. Detailed national-level data and projections serve to improve the spatial detail of the estimates and to highlight the differences between the global and national estimates. Figure 1 illustrates the models and data linkages used in the analysis. The models and data sources used are introduced in the following.

Global IPCC emission scenarios

The global long-term energy and emissions scenarios used in the study are from the IPCC Special Report on Emissions Scenarios (SRES) (Nakićenović *et al*. 2000). The IPCC presented four scenario "families" comprising a total of 40 scenarios, developed with six integrated assessment models. In each family, different assumptions on the global and regional driving forces were assumed (Table 1). The SRES team introduced "marker" scenarios to represent each scenario family. To obtain a wide range of possible futures, scenarios from all main scenario families as well as two variations of the A1 scenario, "Coal-intensive" (A1C) and "Technology" (A1T) (Nakićenović *et al*. 2000), were considered in this study (Carter *et al*. 2004). As this study concentrates on European emissions and their reflections on Finland, the two European models used in the SRES work, IMAGE 2.1 (Alcamo *et al*. 1998, Alcamo *et al*. 2002) and MESSAGE (Riahi and Roehrl 2000, Roehrl and Riahi 2000), were selected for the analysis.

In addition to the global SRES scenarios, air pollutant emission scenarios from the EU AIR-CLIM project coordinated by the University of Kassel were also used in this study. The AIR-CLIM scenarios include further analysis of air pollution control policy options in Europe (Alcamo *et al*. 2002, Mayerhofer *et al*. 2002). The AIR-CLIM project considered the A1 and B1 scenarios of the IPCC. Further sulphur and nitrogen oxides scenarios for European countries were developed within AIR-CLIM, taking into account both present emission policies and plausible further emission reduction policies. Also the impacts of climate change on the atmospheric transformation and transportation of air pollutants were assessed in the project with the help of the ECHAM4 general circulation model (Mayerhofer *et al*. 2002).

Deposition modelling

Deposition was estimated with the regional atmospheric transport and deposition model DAIQUIRI (Deposition, AIr QUality and Integrated Regional Information) (Syri *et al*. 1998, Kangas and Syri 2002). DAIQUIRI calculates annual deposition from Finnish sources with a resolution of 0.25° × 0.125°, which is about 14 km × 14 km in southern Finland. DAIQUIRI includes regional source-receptor matrices developed in collaboration with the Finnish Meteorological Institute (FMI). The regional nitrogen source-receptor matrices are calculated from the results of the FMI-RM model of the FMI, which is a Eulerian-type grid model (Hongisto 1992, 1993), and the regional source-receptor matrices for sulphur are from earlier work of the FMI (Johansson *et al*. 1990).

Long-range transboundary air pollution in Europe was modelled using the results of the Lagrangian acid deposition model developed and employed by the Meteorological Synthesizing Centre-West of the UN/ECE EMEP programme (EMEP/MSC-W 1998). The EMEP model has been widely used in the development of European control strategies of transboundary air pollution during the 1980s and 1990s (Alcamo *et al*. 1990, Schöpp *et al*. 1999). The EMEP model is a receptor-oriented Lagrangian-type trajectory model. Along the trajectories, differential equations describing the mass balance for pollutants take into account emissions, chemical reactions and deposition. The model uses a horizontal grid

Table 1. Some main features of the SRES scenario families used in this study (Nakićenović *et al*. 2000).

Scenario	Population growth	Economic growth	Technological development	Environmental protection
A1	low	very rapid	rapid	intermediate
A2	high	varies between regions	slow	weak
B1	low	rapid	rapid	strong
B2	moderate	moderate	moderate	strong

size of 150 km × 150 km covering the whole of Europe, and it has one vertical layer of variable height corresponding to the atmospheric mixing layer. The model calculates concentrations and depositions as grid square averages and as country-allocated import-export budgets. The source-receptor matrices calculated from the results of the EMEP Lagrangian transport model are incorporated in the DAIQUIRI framework for the estimation of long-range transported deposition.

The plausible impacts of climate change on the atmospheric transformation and transportation of air pollutants and thus on future deposition to Finland were assessed using the results of the AIR-CLIM project (Mayerhofer *et al*. 2002). In the AIR-CLIM project, the ECHAM model was used to assess the impacts of climate change on deposition in Europe by the 2040s. The climate data used was from an earlier study run for the IPCC IS95a scenario (Cubasch *et al*. 1999), featuring a doubling of CO_2 concentration levels from the pre-industrial levels and a global temperature increase of about 2 K from the 1970s to the 2040s. In the AIR-CLIM work, the six-hourly climate data from the ECHAM model was used as input to the EMEP model described above.

Sulphur and nitrogen oxides emission scenarios

European legislation concerning sulphur and nitrogen oxides emissions

In Europe, long-range transboundary air pollution has been combatted in the context of the Framework Convention on Long-Range Transboundary Air Pollution (CLRTAP) of the United Nations Economic Commission on Europe (UN/ECE). It covers practically all European countries, including the areas of the former Soviet Union. The Gothenburg Protocol, signed in 1999, sets emission ceilings for acidifying, eutrophying and ozone-forming air pollutants to be achieved by the year 2010 (UN/ECE 1999).

Complementary to the CLRTAP work, the EU has recently published significant new directives regulating air pollutant emissions. The National Emission Ceilings (NEC) directive (EU 2001a) sets country-specific ceilings for total annual emissions of sulphur, nitrogen oxides (NO_x), ammonia and volatile organic compounds (VOCs) to be achieved by the year 2010. In parallel with the NEC directive, the EU has revised the Large Combustion Plants (LCP) directive, which regulates the emissions from all combustion plants greater than 50 MW_{th} (EU 2001b). Together, the NEC and the revised LCP directives are the main instrument towards achieving the Union's long-term air quality objectives, i.e., the elimination of excess acid deposition and reduction of tropospheric ozone below levels harmful for human health and vegetation (EU 2001a). The NEC directive is expected to reduce sulphur and NO_x emissions by 80% and 51%, respectively, from 1990 to 2010 in the EU-15 region.

Emissions from the transport sector have been regulated in the context of the Auto-Oil programmes in the EU. The emission specifications for new cars, heavy-duty vehicles, off-road vehicles, etc. are progressively tightened (European Commission 2000). Altogether, these directives imply very significant reductions in harmful air pollutant emissions (excluding greenhouse gases) from the transport sector in the near- and medium-term future.

Long-term emission scenarios for European regions

Transitions in technology determine to a major extent the future development of not only the emissions of greenhouse gases, but also of other air pollutants. For instance, sulphur emissions depend on the use of sulphur-containing fuels, mainly coal and oil, and on the flue gas cleaning technologies in place. Nitrogen oxides, in turn, are formed in all combustion processes. The future development of nitrogen oxide emissions depends on the amount of conventional combustion technologies in use and on the types of reduction technologies in place. Presently, the transportation sector is responsible for a major part of total NO_x emissions in many industrialised countries. However, in many regions, including the EU, NO_x emissions from the transport sector are decreasing rather rapidly due to the continuing penetration of efficient catalytic converters into the vehicle fleet (European Environment Agency 2002).

In the long-term SRES A1 scenarios, the rapid technological development results in an increase of either modern coal-based technologies (A1C) or gas and non-fossil supplies of energy (A1T). In the A1C scenario, there would be a considerable growth in sulphur emissions from the OECD90 countries until 2030. In the A2 scenario, in turn, the sulphur emissions from the countries of the former Eastern Europe would grow until the 2060s due to the slow technological progress and increased coal use assumed. NO_x emissions from the OECD90 countries would grow steadily in the A1C and A2 scenarios until the year 2100. With all the other scenarios studied, they would start to decrease around 2040, at the latest.

For the countries of the former Eastern Europe and the Soviet Union, the A1C and A2 scenarios studied assume a strong growth in both sulphur and NO_x emissions from the present. Sulphur emissions would eventually start to decrease in the A1C and A2 scenarios in the latter half of the century. The other scenarios studied foresee a strong decrease in sulphur emissions from the present. Only in the B1 scenario modelled with IMAGE do NO_x emissions decrease significantly from the present.

The A1C and A2 scenarios are quite pessimistic in the estimates of the development of both sulphur and NO_x emissions. For sulphur emissions, efficient flue-gas cleaning technologies are state-of-the-art technology and required by legislation in most European countries by today. For nitrogen oxides, modern combustion technologies are usually "Low-NO_x" combustion technologies with reduction efficiencies around 50%. In addition, add-on technologies with reduction efficiencies around 70%–90% (SCR or SNCR technologies) are commercially available and also required by legislation in countries with advanced environmental legislation. Also the EU Large Combustion Plants (LCP) directive requires the use of advanced NO_x control equipment after 2016 in large power plants (EU 2001b).

In addition to the global SRES scenarios, also air pollutant emission scenarios from the AIR-CLIM EU project coordinated by the University of Kassel were used in this study. The AIR-CLIM scenarios include further analysis of air pollution control policy options in Europe in the A1 and B1 scenarios (Alcamo *et al*. 2002, Mayerhofer *et al*. 2002). Further sulphur and nitrogen oxides scenarios for European countries were developed within AIR-CLIM, taking into account both present emission policies and plausible further emission reduction policies. The "Present air pollution policies" scenarios were based on the legislative developments described above (indicated by "-p" in Tables 2 and 3). The "Advanced air pollution policies" scenarios (indicated by "-a" in Tables 2 and 3) for Europe were developed by assuming that the sulphur and NO_x emission reduction rates would gradually approach the estimated maximum feasible values of 95% and 85%, respectively (Mayerhofer *et al*. 2002).

Table 2. SO_2 emissions in the EU-15 and in non-EU countries as used in the study (in Mtonnes SO_2).

	1990**		2020		2050		2100	
	EU-15	Other European	EU-15	Other European	EU-15	Other European	EU-15	Other European
A1C	16.4	19.5	5.9	11.3	3.6	12.8	1.4	11.0
A1T	"	"	1.0	6.6	0.0	5.4	1.0	4.1
A1-p*	"	"	4.1	10.4	3.1	8.5	2.5	5.1
A1-a*	"	"	2.3	9.1	1.0	5.1	0.8	1.4
A2	"	"	2.1	11.6	0.7	19.0	2.0	5.9
B1-p*	"	"	3.9	10.4	1.8	7.9	0.6	2.2
B1-a*	"	"	2.1	9.4	0.5	5.1	0.2	1.1
B2	"	"	2.3	5.0	1.4	4.1	1.2	5.1

* Mayerhofer *et al.* 2002, ** Vestreng 2001.

The emission scenarios used in this work were derived from the coarser IPCC regional distribution, i.e., OECD90 countries and countries undergoing economic reforms, by taking into account the country- and region-specific emission developments during 1990–2010. Accounting for the expected significant emission cuts by 2010 in European countries resulted in considerably lower relative future emission developments than the original IPCC emissions scenarios for the corresponding larger regions (Nakićenović *et al*. 2000). Tables 2 and 3 present the emission scenarios used in this study.

The emission ceilings set in the EU National Emission Ceilings directive and in the UN/ECE Gothenburg Protocol correspond to a total of 3.9 Mtonnes SO_2 for the EU-15 countries and 11.6 Mtonnes SO_2 for the other European regions to be achieved by 2010. In 1999, emissions were at 6.2 Mtonnes SO_2 in the EU-15 area and approximately 11 Mtonnes SO_2 in the other European regions according to preliminary information (Vestreng 2001).

Correspondingly, the NO_x emission ceilings by 2010 are 6.5 Mtonnes NO_2 for the EU-15 countries and 7.3 Mtonnes NO_2 for the European regions outside the EU-15 included in the Gothenburg Protocol. In 1999, emissions were at 9.9 Mtonnes NO_2 in the EU-15 area and approximately 7.0 Mtonnes NO_2 in the other European regions according to preliminary information (Vestreng 2001).

Emissions of ammonia (NH_3), which contribute to acidification and eutrophication, are expected to decline in Europe by 17% by 2010 from the 1990 situation as a result of the NEC directive and the UN/ECE Gothenburg protocol (UN/ECE 1999). Ammonia emissions are not directly affected by climate policies (Mayerhofer *et al*. 2002).

National-scale projections

In addition to the European-scale emissions scenarios, national-level studies were conducted in order to compare the scenarios derived from global models for Finland with the national-level knowledge and forecasts. Scenarios extending to the year 2020, as developed recently in the context of the preparation of the National climate strategy for Finland, were used for this purpose (Syri *et al*. 2002). Table 4 compares the national emission estimates for 2020 with the SRES and AIR-CLIM scenarios developed here. In addition, the emission ceilings of the UN/ECE and the EU for Finland for 2010 are shown.

The "Baseline" scenario (BAU) illustrates a situation without explicit climate policies, i.e., in line with the SRES storylines. The rapid economic growth and open markets assumed resemble those in the A1 scenarios, and the expanded coal use is broadly consistent with the A1C scenario. The alternative "KIO1" and "KIO2" are not exactly consistent with the SRES scenarios, since they include explicit climate policies for achieving the Kyoto Protocol requirements. However, many of the elements assumed, such

Table 3. NO_x emissions in the EU-15 and in non-EU countries as used in the study (in Mtonnes NO_2).

	1990**		2020		2050		2100	
	EU-15	Other European	EU-15	Other European	EU-15	Other European	EU-15	Other European
A1C	13.3	10.2	7.0	9.8	7.6	20.0	13.3	29.1
A1T	"	"	6.6	8.8	4.2	10.7	1.1	4.9
A1-p*	"	"	6.7	5.3	6.6	5.3	8.4	13.4
A1-a*	"	"	5.1	5.2	3.6	2.9	2.7	1.5
A2	"	"	7.4	8.8	8.4	13.4	12.3	21.5
B1-p*	"	"	6.7	5.3	4.7	5.3	2.1	2.5
B1-a*	"	"	4.8	5.3	2.1	3.7	1.0	0.9
B2	"	"	7.3	8.3	7.7	13.6	5.7	9.5

* Mayerhofer *et al.* 2002, ** Vestreng 2001.

as slower economic growth, a higher and partly environmentally based taxation and emphasised environmental awareness in society resemble those in the SRES B1 and B2 scenarios.

The global scenarios, such as A1T, may overestimate the speed at which the energy system shifts towards other structures in comparison with national-level estimates (Table 4). The sulphur emission scenarios reflect mainly the speed at which transitions between fuels take place. In Finland, industrial processes are a large source of sulphur emissions, which partly explains the different emission reduction speeds between the global and national scenarios. The global and national NO_x scenarios until 2020, in turn, are quite consistent with each other, and the differences in emission amounts reflect mainly the variations in energy and fossil fuel use in the scenarios.

From 2020 onwards, only the IPCC emissions scenarios (Table 4) were used for Finland, with the development following the general EU-15 trends (Tables 2 and 3).

Long-term deposition scenarios for Finland

Based on the emission scenarios described above, long-term deposition scenarios were derived using the DAIQUIRI deposition model. The two locations chosen reflect the differences in deposition patterns between southern and northern Finland (*see* Fig. 2). Southern Finland is strongly affected by deposition from neighbouring areas, central Europe and domestic emissions, whereas in central and northern Finland deposition levels are much lower and dominated by long-range transboundary air pollution. The only exception is north-eastern Lapland, where the large metal smelter activities in the Russian Kola peninsula are dominating sources of sulphur deposition. As none of the emission scenarios used predict dramatic future increases in Finnish emissions, these basic patterns in the origin of deposition will remain in all the scenarios.

Between the base year of the study, 1990, and the present, significant changes in deposition levels have already taken place in Finland. Everywhere in Europe, sulphur emissions have been cut efficiently, resulting in a considerable decrease in deposition to Finnish sites (Fig. 2). Due to the international reduction agreements, this development is expected to continue in the future. Only in the fossil-intensive scenarios A1C and A2, deposition levels would remain at approximately the present level. This is significantly below the 1990 levels, not only at the sites shown in Fig. 2, but everywhere in Finland. Towards the end of the century, the trends would decline further also in the A1C and A2 scenarios.

In most studied scenarios, sulphur deposition is expected to decline everywhere in Finland in the future (Fig. 3). The "Advanced emission control policies" scenarios of the AIR-CLIM project result in clear decreases in sulphur deposition everywhere in Finland. The IPCC A1T scenario, with the assumed rapid technological development and shifting to non-fossil fuels, would imply even larger decreases of sulphur deposition in the long term.

For nitrogen oxides deposition in Finland, several scenarios are considerably more pessimistic than those for sulphur deposition. The SRES A1C and A2 scenarios imply higher deposition levels for Finland than in 1990. Also with the B2 and even the A1T scenario the present

Table 4. SO_2 and NO_x scenarios used for Finnish emissions (EU 2001a, UN/ECE 1999, Mayerhofer *et al.* 2002, Syri *et al.* 2002) (in kilotonnes SO_2/NO_2).

	1990**		2000**		2020	
	SO_2	NO_x	SO_2	NO_x	SO_2	NO_x
IPCC						
A1C	260	300	75	208	167	179
A1T	260	300	75	208	27	169
A1-p*	260	300	75	208	133	150
A1-a*	260	300	75	208	76	115
A2	260	300	75	208	59	189
B1-p*	260	300	75	208	129	150
B1-a*	260	300	75	208	71	109
B2	260	300	75	208	65	187
National						
BAU	260	300	75	208	117	182
KIO1	260	300	75	208	79	160
KIO2	260	300	75	208	84	164
Ceilings***						
UN/ECE	260	300	75	208	116	170
EU	260	300	75	208	110	170

* Mayerhofer *et al.* 2002 , ** Statistics Finland 2002, *** originally for 2010.

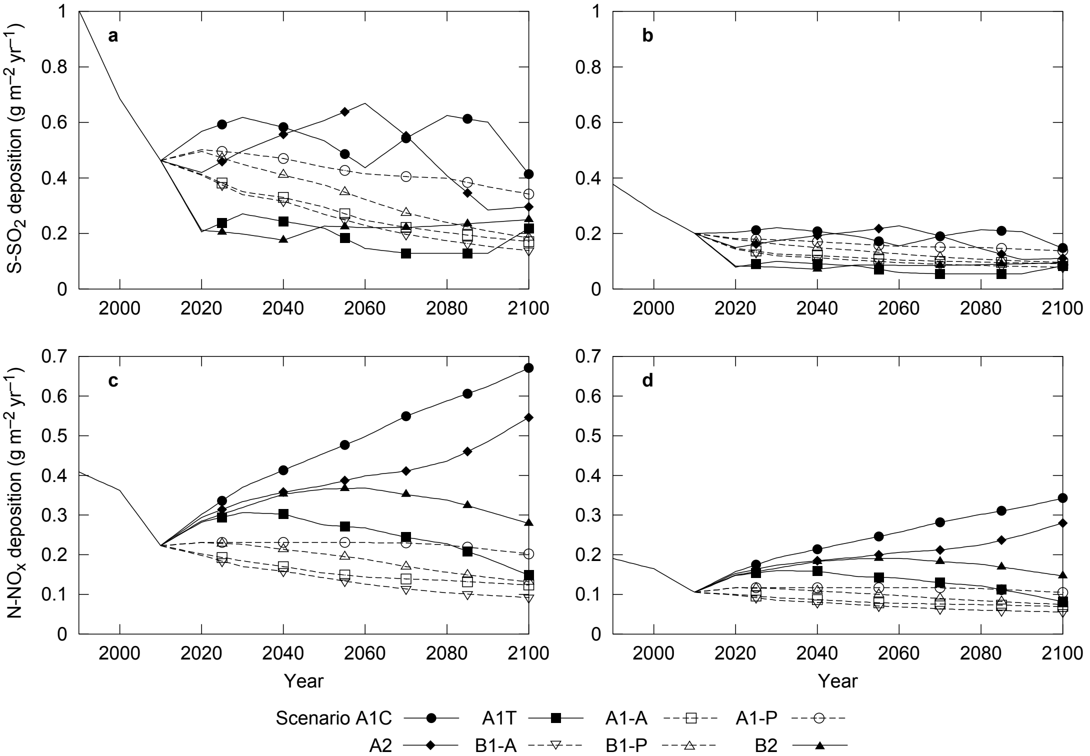

Fig. 2. Sulphur (S-SO$_2$: **a** and **b**) and nitrogen (N-NO$_x$: **c** and **d**) deposition time series with the scenarios studied for Helsinki (60°25´N, 24°58´E) (**a** and **c**) and for Rovaniemi 66°29´N, 25°41´E) (**b** and **d**).

downward trend in nitrogen oxides deposition would reverse in the next decades. The growing trend in nitrogen oxides deposition in the A1C and A2 scenarios would continue throughout the century. In the fossil-intensive scenarios A1C and A2, the spatial patterns in the origin of nitrogen oxides deposition would change considerably. Whereas emissions in the present EU-15 countries would increase slowly from the present level, emissions from Eastern Europe and the former Soviet Union would grow dramatically (Fig. 4c). In all the scenarios of the AIR-CLIM project, nitrogen oxides emission scenarios reflect much more realistically the recent developments in NO$_x$ emission control technologies and policies, resulting in further decreasing trends of deposition.

The AIR-CLIM results of the plausible impacts of climate change on sulphur and nitrogen oxides deposition to Finland are shown in Figs. 3b and 4b, respectively. The main differences occur for the coastal areas in the southern and western parts of the country, where deposition is reduced via the changes in climate. For nitrogen oxides, a raised temperature can increase the share of atmospheric nitrogen in particulate form, which lengthens the average atmospheric transportation distance. Future changes in precipitation, in turn, affect the amount of wet deposition and the pollutant concentrations. The changed climate alters also the nearby deposition, as temperature increases and the surface resistance decreases. This increases the rate of dry deposition. This mechanism is exemplified in north-eastern Finland in the vicinity of the Russian sulphur emitting smelter industries.

In general, the results indicate that future changes in emissions are a considerably more significant factor than the expected meteorological changes in determining the future deposition levels. However, in a single medium-term climate simulation with one model, both natural variability and model properties may mask the outcome significantly. Further research with more models and scenarios (including longer-term scenarios) would be needed for robust estimates.

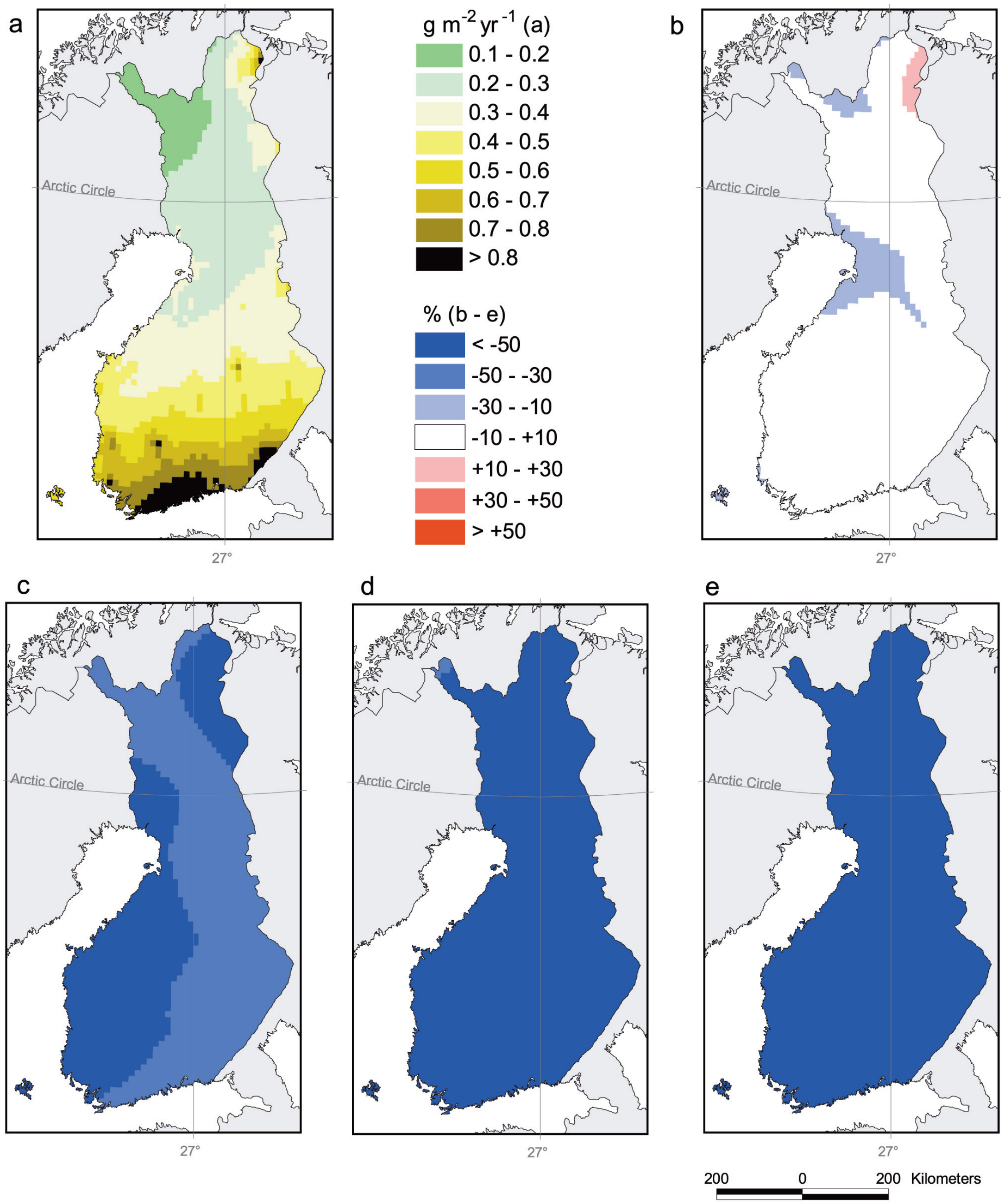

Fig. 3. Sulphur (S-SO$_2$) deposition (**a**) in 1990 and (**b**–**e**) the difference taking place by the year 2050 from 1990 in different scenarios studied. In panel **b**, the plausible impact of climate change by the 2040s is shown. Panel **c** shows deposition with the A1C scenario. The AIR-CLIM “A1-present policies” scenario is depicted in panel **d**. Panel **e** shows the AIR-CLIM “B1-present policies” scenario.

The modelled depositions presented here, which result from alternative global and regional emissions scenarios, are aimed to indicate the relative differences in environmental loadings caused by alternative future pathways. Due to the long calculation chain with atmospheric models and the uncertainties involved they should not be regarded as exact estimates for the locations

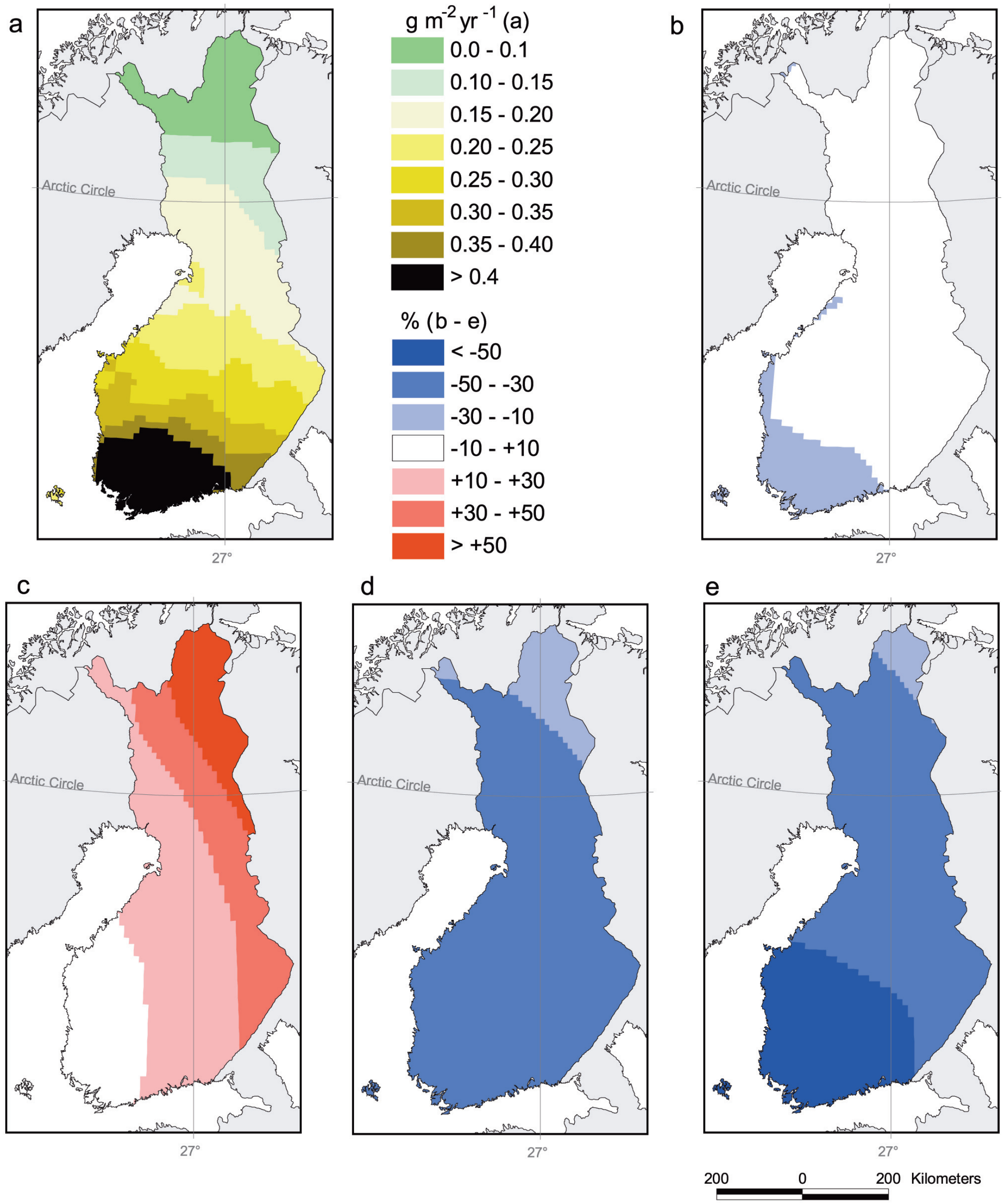

Fig. 4. Nitrogen (N-NO$_x$) deposition (**a**) in 1990 and (**b**–**e**) the difference taking place by the year 2050 from 1990 in different scenarios studied. In panel **b**, the plausible impact of climate change by the 2040s is shown. Panel **c** shows deposition with the A1C scenario. The AIR-CLIM "A1-present policies" scenario is depicted in panel **d**. Panel **e** shows the AIR-CLIM "B1-present policies" scenario.

presented (e.g. Fig. 2). Syri *et al*. (2000) evaluated the uncertainties involved in acidification modelling in Finland. Both modelled deposition values and ecosystem critical loads were found to contribute significantly to the total ecosystem protection uncertainty.

Discussion

The most pessimistic long-term SO_2 and NO_x scenarios of the IPCC appear not very probable for Europe when compared with the recent European emission control legislation and reduction agreements and with the present status of add-on control technologies. The increased sulphur emissions in the future would imply a poor economical situation for Europe, as efficient flue gas desulphurisation is already state-of-the-art technology and mostly required by legislation. This contrasts with the A1 storyline, which assumes rapid economic growth. Presently, about half of the NO_x emissions in Europe are from the transport sector. However, both the total emission trend and the share of transport in total NO_x emissions are declining as catalytic converters are penetrating the vehicle fleet. Similarly, primary NO_x control technologies are state-of-the-art technologies in stationary sources, and more efficient secondary catalytic methods are also penetrating large sources. Therefore, significant future increases of total NO_x emissions would imply that these already mature technologies would not be used in spite of large evidence on the harmfulness of the emissions. Based on these considerations, Table 5 presents an indicative ranking of the probabilities for the IPCC Air pollutant scenarios for European regions. The emission scenarios developed in the AIR-CLIM EU project are also included (Alcamo *et al*. 2002, Mayerhofer *et al*. 2002).

Conclusions

In this study, long-term scenarios of sulphur and nitrogen oxides deposition were developed for Finland based on the IPCC Special Report on Emissions Scenarios (SRES). The SRES scenarios were found to be mostly suitable for describing the approximate impacts of long-term global socio-economic and technological trends on large-scale air pollution. However, the future decoupling between fossil fuel use and sulphur and nitrogen oxides in the IPCC scenarios was found to be pessimistic in comparison with developments already observed in Europe.

Table 5. Qualitative probabilities for the European SO_2 and NO_x scenarios studied (Nakićenović *et al.* 2000), based on recent advances in air pollution control technology and legislation (EU 2001a, 2001b, European Commission 2000, UN/ECE 1999). The terms "present" and "advanced" relate to the assumed SO_2 and NO_x control policies (Mayerhofer *et al.* 2002).

	OECD Europe of 1990		Former Eastern Europe	
Scenario	SO_2	NO_x	SO_2	NO_x
A1C	improbably pessimistic in the short term	improbably pessimistic	improbably pessimistic	improbably pessimistic
A1T	optimistic	feasible	feasible	feasible, pessimistic
A1-present*	pessimistic	feasible	feasible	pessimistic in the long term
A1-advanced*	feasible	feasible	feasible	feasible
A2	mostly feasible	improbably pessimistic	improbably pessimistic	improbably pessimistic
B1-present*	feasible, pessimistic in the short term	feasible	feasible	feasible
B1-advanced*	mostly feasible	feasible	feasible	feasible
B2	feasible	feasible, pessimistic	feasible	feasible, pessimistic

* Mayerhofer *et al.* 2002.

In the light of recent air pollution reduction legislation in Europe, increasing deposition trends both for Europe and for Finland appear unlikely. This is not taken into account in the SRES scenarios, especially in the fossil-fuel intensive A1C and A2 storylines. In all the other scenarios studied, the future sulphur and nitrogen oxides deposition trends in Finland are either approximately constant or decreasing, which is well in line with the recent European air pollution control policy developments. In the light of the recent developments in both sulphur and nitrogen oxides emission control technologies and policies, not even the "Advanced emission control policies" scenarios, as developed in the AIR-CLIM EU project (Alcamo *et al*. 2002, Mayerhofer *et al*. 2002) can be regarded as overly optimistic.

This study indicated that large-scale studies, such as the IPCC global emissions scenarios work, may not as such be suitable for describing future developments for smaller regions. For more robust quantitative estimates of emissions and environmental impact scenarios, comparisons and adjustments with national and regional developments also proved necessary. As especially sulphate aerosols are also important regional climate agents, estimates of the future development of sulphur emissions in global climate scenario modelling also have significant implications for the resulting climate change projections. Overestimated future levels of sulfate aerosols result in underestimated climate change scenarios.

The preliminary analysis of the AIR-CLIM project (Mayerhofer *et al*. 2002) implied that in the next decades, climate change is not expected to have large impacts on acidifying and eutrophying deposition in northern Europe. However, further research with more models and scenarios (including longer-term scenarios) would be needed for robust estimates. In addition to the impacts of a changing climate on deposition, the impacts of transcontinental atmospheric pollution transportation would merit more attention.

Climate change is also expected to change the tolerance of ecosystems against pollution loading and parameters affecting the fate of pollutants in the soils, such as the accumulation and leaching of nutrients (e.g. Posch 2002). These aspects were not analysed within this study, but should be subjects of further work. More research, both experimental and theoretical, on ecosystem behaviour and recovery from past pollution loading under varying deposition and changing climatic conditions would be needed.

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