INTEGRATED ASSESSMENT OF EUROPEAN AIR POLLUTION EMISSION CONTROL STRATEGIES

Wolfgang Schöpp, Markus Amann,
Janusz Cofala, Chris Heyes, and Zbigniew Klimont
International Institute for Applied Systems Analysis
Laxenburg, Austria

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International Institute for Applied Systems Analysis, Laxenburg, Austria
Tel: +43 2236 807 Fax: +43 2236 73148 E-mail: publications@iiasa.ac.at

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Integrated assessment of European air pollution emission control strategies

Wolfgang Schöpp *, Markus Amann, Janusz Cofala, Chris Heyes, Zbigniew Klimont

International Institute for Applied Systems Analysis (IIASA) A-2361 Laxenburg, Austria

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Abstract

The RAINS (Regional Air Pollution Information and Simulation) model (Alcamo et al., 1990. The RAINS Model of Acidification. Science and Strategies in Europe. Kluwer, Dordrecht) was developed at IIASA as an integrated assessment tool to assist policy advisors in evaluating options for reducing acid rain. Such models help to build consistent frameworks for the analysis of abatement strategies. They combine scientific findings in the various fields relevant to strategy development (economy, technology, atmospheric and ecological sciences) with regional databases. The environmental impacts of alternative scenarios for emission reductions can then be assessed in a consistent manner ('scenario analysis'). This paper outlines the current stage in the development of an integrated assessment model for acidification and tropospheric ozone in Europe and explores the likely impacts of the currently agreed policy measures for controlling emissions on acidification and ground-level ozone. © 1998 Elsevier Science Ltd. All rights reserved.

Keywords: Integrated assessment; Interactive simulation; Environmental science; Computer software; Ozone; Acidification

Software availability

Program title:	RAINS 7 Europe
Developers:	Wolfgang Schöpp et al.
Contact address:	Wolfgang Schöpp, International Institute for Applied Systems Analysis (IIASA) A-2361 Laxenburg, Austria; e-mail:schoepp@iiasa.ac.at
First available:	1995 (Update including ozone: End of 1998)
Hardware required:	Compatible personal computer 486 or higher
Software required:	Windows 95 or Windows NT
Program language:	C + +
Availability and cost:	See: http://www.iiasa.ac.at/Research/TAP/rains—europe/index.html

1. Introduction

In recent years the European implementation of the RAINS model has been used to support the negotiations on an updated Sulfur Protocol under the Convention on Long-range Transboundary Air Pollution (UN/ECE, 1994). RAINS and other integrated assessment models indicated that flat-rate, source-oriented approaches, as used in earlier protocols, do not necessarily produce cost-effective solutions (Hordijk, 1995; Tuinstra et al., 1998; Gough et al., 1998). For the first time, the Second Sulfur Protocol made use of an alternative, effect-oriented approach, in which the extent of emission reductions is guided by the impacts that emissions from a given source have on sensitive ecosystems.

At the moment, highest priority in Europe is being given to the development of a strategy for a Second NO_x Protocol. Reducing nitrogen emissions based on environmental effects is a rather complex process. The interrelation of several environmental effects (acidification, eutrophication, vegetation damage and threats to human health caused by tropospheric ozone) constitutes a multi-effect, multi-pollutant problem.

This paper provides a brief overview of the RAINS

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* Corresponding author. Tel.: + 43 2236 807 309; fax: + 43 2236 71 313; e-mail: schoepp@iiasa.ac.at

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model and presents some example applications. After outlining the general modeling approach the recent model extensions for ground-level ozone are discussed. Section 4 presents an outlook on emission levels expected for 2010 as a result of current policy, while the remaining sections explore the scope for cost-optimized further improvements of air quality in Europe.

2. An overview of the RAINS model

In order to create a consistent and comprehensive picture of the options for simultaneously addressing these environmental problems the RAINS model considers emissions of SO_2, NO_x, NH_3 and volatile organic compounds (VOC). A schematic diagram of the RAINS model is displayed in Fig. 1.

The European implementation of the RAINS model incorporates databases on energy consumption for 45 regions in Europe, distinguishing 21 categories of fuel use in six economic sectors. The time horizon extends from the year 1990 up to the year 2010. Emissions of SO_2, NO_x, NH_3 and VOC for 1990 are estimated, based on information collected by the CORINAIR inventory of the European Environmental Agency (EEA, 1996). Options and costs for controlling emissions of the various substances are represented in the model by considering the characteristic technical and economic features of the most important emission reduction options and technologies (Amann, 1990; Amann and Cofala, 1995; Klaassen, 1994). Atmospheric dispersion processes over Europe for sulfur and nitrogen compounds are modeled, based on results of the European EMEP model developed at the Norwegian Meteorological Institute (Barret and Sandnes, 1996). For tropospheric ozone, source–receptor relationships between the precursor emissions and the regional ozone concentrations are derived from the EMEP photo-oxidants model (Simpson, 1993). The RAINS model incorporates databases on critical loads and critical levels compiled at the Coordination Center for Effects (CCE) at the National Institute for Public Health and Environmental Protection (RIVM) in the Netherlands (Downing et al., 1993; Posch et al., 1995).

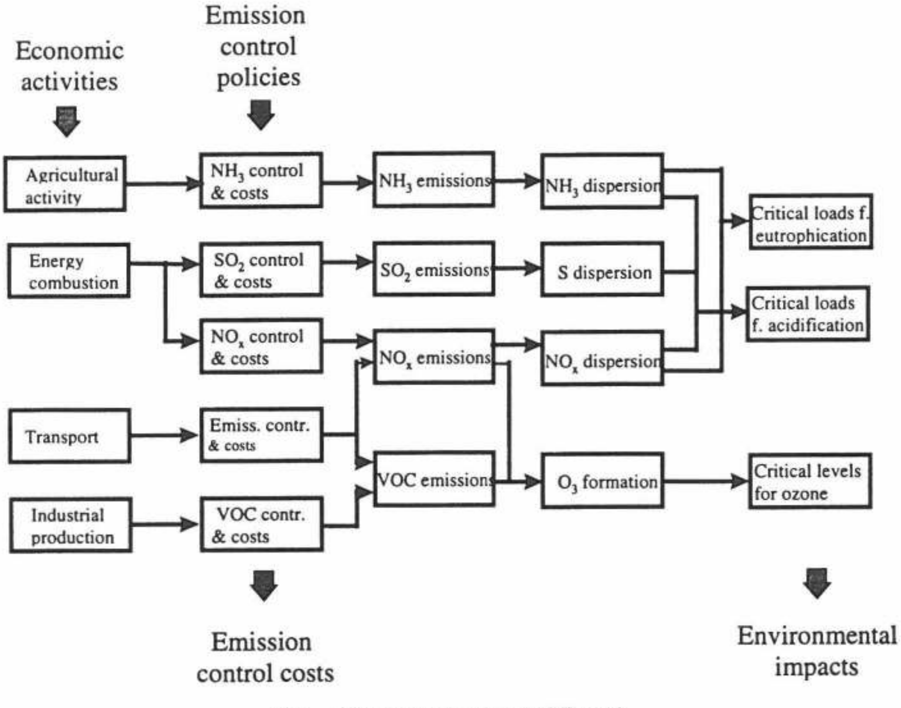

Fig. 1. Schematic flowchart of the RAINS model.

3. A 'reduced-form' model for tropospheric ozone

3.1. Introduction

Integrated assessment models are typically used to perform numerous scenario runs for analyzing costs and benefits from a wide range of control strategies and to conduct comprehensive uncertainty and robustness analyses, which are essential for deriving solid conclusions. Optimization analysis, i.e. the optimization of the entire chain from the sources of emissions, through the costs for controlling them, up to the regional impacts of pollutants, has proven to be a powerful feature in the integrated assessment process for the Second Sulfur Protocol.

Thus, the source–receptor relationships describing the dispersion of emissions from a source to the various receptors must be computationally efficient, requiring sufficiently simple formulations of the underlying models. While for sulfur and nitrogen compounds linear relationships have proven to be sufficient to describe the long-term and long-range characteristics of atmospheric dispersion (enabling the use of linear 'source–receptor matrices' in integrated assessment models), for tropospheric ozone the situation is more complex.

Most of the available models for ozone formation are process-oriented and contain a considerable degree of detail of the chemical mechanisms and meteorological factors relevant for ozone formation. Consequently, their computational complexity makes it impossible to use them directly within the framework of an integrated assessment model. In order to overcome this gap, an attempt has been made to construct a 'reduced-form' model, using statistical methods to summarize the reaction of a more complex 'reference' model.

3.2. Effects of ozone

Effect-based research in Europe suggests using a long-term criterion as the no-damage threshold for vegetation (Kärenlampi and Skärby, 1996). In particular, for natural ecosystems and crops the integral of hourly ozone levels exceeding the 40 ppb level, accumulated over a period of three months (May to July) was proposed (the 'AOT40'). The 'critical level' to protect natural vegetation and crops is currently set at 3000 ppb h. As a consequence, integrated assessment models and the source–receptor relationships should also be able to address the long-term ozone exposure over a multi-month period.

The simplified source–receptor relationships need to be able to predict changes in ozone at a receptor grid resulting from emission abatement strategies adopted in various European countries. Emission estimates at a national level were considered to be the most appropriate for this purpose, and the regression model uses national, annual emissions of NO_x and VOCs as explanatory variables. Initial versions of the model discussed in this paper adopted the mean early afternoon ozone concentration over the six-month summer period as the response variable to be predicted. Subsequently, models of the same form were also developed for AOT40 and AOT60 measures. It is assumed that the 60 ppb threshold is appropriate to represent health effects. This AOT60 indicator has been introduced purely for practical modeling reasons. Given the current knowledge it is not possible to link any AOT60 value with a certain risk to health. The agreed interpretation is that if the AOT60 is > 0, the WHO criterion (WHO, 1998) is exceeded at least once a year.

3.3. Atmospheric model for ozone

Basic ideas about which terms should be included in the simplified model were developed from the published results of studies using the EMEP ozone model. Experience of this model's behavior was gained during earlier IIASA studies into the possibilities of developing a simplified regression model for predicting daily ozone concentrations, which made use of non-parametric methods. The results suggested that a multi-dimensional quadratic spline could be used to reproduce the main features of the relationship between ozone and the emissions of its precursors. The simplified 'daily' model also made use of the concept of 'effective' emissions, suggested by studies with the EMEP model (Simpson, 1995) which showed that exchange processes between the boundary layer and the free troposphere could have a significant impact on the final ozone concentrations. To allow for these effects, emissions along the trajectory were weighted by the amount of dilution that subsequently takes place within the air mass (Simpson, 1995) to give the dilution-weighted or 'effective' NO_x and VOC emissions used as variables in the regression model.

For the full version of the reduced-form model discussed in this paper an evaluation in terms of the AOT40 and AOT60 measures was performed. In the following equations l indicates the different thresholds, 40 or 60 ppb, and the period for which the AOT is calculated. Experiments led to the conclusion that the following linear regression model contained sufficient information for the present purpose:

$$AOT_{lj} = k_{jl} + \sum_{i=1}^{M} (a_{ijl}v_i + b_{ijl}n_i + c_{ijl}n_i^2) + \alpha_{jl}\overline{en}_j^2 + \overline{en}_j \sum_{i=1}^{M} d_{ijl}v_i$$

where the AOT_l at receptor j (AOT_{lj}) is assumed to be a function of the non-methane VOC and NO_x emissions,

v_i and n_i respectively, from each emitter country i, and the mean 'effective' NO_x emissions experienced at the receptor over the period in question (en_j).

$$en_j = \sum_{i=1}^{M} e_{ij} n_i$$

M is the number of emitter countries considered. The coefficients a_{ijl}, b_{ijl}, c_{ijl}, d_{ijl} and α_{jl} are estimated by a linear regression, and n_i, v_i and en_j are used as variables. The coefficients e_{ij}, a_{ijl} and b_{ijl} may also be regarded as a composite source–receptor matrix.

The formulation of the reduced-form model given in the equation above has been used in the construction of models for 598 European receptor grids. Details of the approach can be found in (Heyes et al., 1996). It is of interest to relate the terms of the equation to the physical and chemical processes that determine ozone formation in the atmosphere. Possible interpretations are:

k_{jl}	includes the effects of background concentrations of O_3 and its precursors, and natural VOC emissions;
$a_{ijl}v_i$	provides the linear country-to-grid contribution from VOC emissions in country i, allowing for meteorological effects;
$b_{ijl}n_i$	provides the linear country-to-grid contribution from NO_x emissions in country i, allowing for meteorological effects;
$\alpha_{jl}en_j^2$	takes account of the average non-linearity (in the O_3/NO_x relationship) experienced along trajectories arriving at receptor j and any non-linear effects local to that receptor;
$c_{ijl}n_i^2$	serves essentially as a correction term to allow for non-linearities occurring close to high NO_x emitter countries;
$d_{ijl}en_jv_i$	allows for interactions between NO_x and VOCs along the trajectories;
$e_{il}n_i$	provides the linear country-to-grid contribution from NO_x emissions in country i, assuming no chemical reaction or dry deposition takes place.

3.4. *Validation of the reduced form ozone model*

The reduced-form model was evaluated against a range of independent emission scenarios. As an example, Fig. 2 compares the AOT40 values obtained from a run of the full EMEP model with the results of the reduced-form model for the NO_x and VOC emissions of the 'Current Legislation' scenario (CLE) described in Section 4.1. Although the fit appears good, there may be a problem in using a linear regression for a truncated problem (threshold of 40 ppb). However, as long as the interest is focused on exceedances above the no-damage 'critical level' of 3 ppm h, this can be neglected.

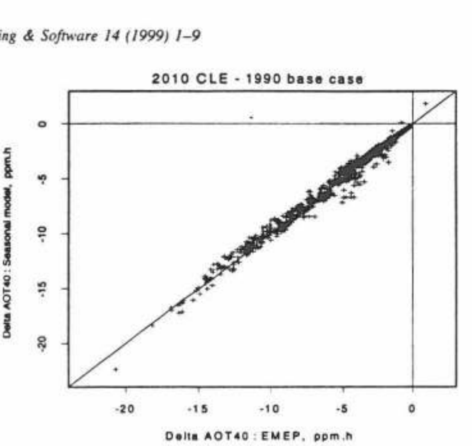

Fig. 2. Comparison of the ozone levels (AOT40) between the results of the full EMEP model and the reduced from model.

4. An application of the rains model

This section will use the RAINS model to explore the changes in NO_x emissions, taking into account the development of future energy and transportation systems and the implications of current NO_x-related emission control legislation in Europe. Subsequently, the impacts on the achievement of acidification-related critical loads and regional ozone levels are analyzed.

4.1. *Future levels of NO_x emissions in Europe resulting from the current legislation*

The projection of future NO_x emissions in Europe is based on forecasts of economic activity and scenarios of energy consumption. For the EU countries the 'Conventional Wisdom' scenario (DGXVII, 1996) and for other countries the so-called 'Official Energy Pathways', as submitted by the individual countries to the UN/ECE Energy Data Bank (UN/ECE, 1995), were used as energy scenario. Whenever forecast data were either incomplete or missing, available short-term projections have been extrapolated with the use of a simple energy model.

These energy data, together with the emission factors provided in the CORINAIR inventory (EEA, 1996) and the information on emission control measures required by the various pieces of legislation, have been used to simulate the effects of emission control policies on emission levels.

The 'current legislation' (CLE) scenario assumes the

Table 1
NO_x emission control measures assumed in the current legislation (CLE) scenario

Stationary sources:
- Primary measures (combustion modification) on new large power boilers
- Use of primary and secondary measures (selective catalytic reduction) according to country-specific emission regulation for industrial and power plant sources

Mobile sources:
- EU and EFTA countries: Car catalytic converters, EURO-I and EURO-II norms for heavy-duty vehicles, Auto/Oil standards after the year 2000, EU standards for off-road vehicles.
- Central European countries (Czech Republic, Hungary, Poland, Slovak Republic, Slovenia): legislation consistent with EU EURO-I and EURO-II controls with three to five years delay
- Other east European countries and Russia: UN/ECE legislation

successful implementation of all legal instruments relating to air pollution control that are currently in force in each country. These include international agreements, such as the Sulfur- and NO_x-Protocols under the Convention on Long-range Transboundary Air Pollution (e.g. UN/ECE, 1994) and (for EU Member States) the various Directives of the European Union on fuel quality and on large combustion plants. For the transport sector it has been assumed that the current EU standards, together with the standards proposed by the Auto/Oil Programme (EC, 1996) will be enforced in all EU countries as well as in Norway and Switzerland (EFTA countries). For other countries the scenario assumes the implementation of the UN/ECE standards and, if stricter, national emission limits. A number of countries in Central Europe already demand controls on transport sources similar to the EU specifications (catalytic converters on cars, EURO-I and EURO-II norms for trucks). Table 1 summarizes the emission control measures considered in the CLE scenario.

Table 2 presents estimates of NO_x emissions for the year 1990 and for the CLE scenario in the year 2010. In 1990, official inventories suggest 22 million tons of NO_x emissions in Europe, with 44% caused by mobile sources. Despite the projected growth in transport volumes, current legislation is expected to decrease total NO_x emissions to about 14 million tons in 2010, i.e. by 38%. The tighter emission standards for mobile sources applied in the countries of the European Union will result in higher reductions in the EU and EFTA countries (− 49%) compared to the Central and Eastern European countries (CEE). Costs of NO_x controls implied by this scenario are slightly higher than 30 billion ECU/a.

Table 2
Emissions of NO_x for 1990 and the current legislation scenario for 2010

Country group	NO_x emissions (million tons)		
	1990	2010	
EU + EFTA	13.8	7.1	− 49%
CEE, of which:	8.3	6.7	− 19%
Accession countries	3.8	2.4	− 36%
Russia	2.7	2.7	− 0%
Total Europe	22.1	13.8	− 38%

Emissions from sea areas are not included.

4.2. *Impacts on acidification*

Rather than predicting actual environmental damage, the RAINS model compares acid deposition against the critical loads of the various ecosystems in Europe. Critical loads are defined as the maximum (long-term) level of exposure of one or several pollutants below which no harmful effects occur to sensitive ecosystems. In a coordinated international effort critical loads have been mapped for the natural and semi-natural ecosystems in Europe, i.e. including forests, lakes, heathland, raised bogs, etc., but excluding agricultural areas, built-up land, and other, non-natural use of land (Posch et al., 1995). The comparison of acid deposition resulting from a particular emission control scenario with critical loads makes it possible to judge whether sustainable conditions can be met by a specific emission control strategy.

In 1990 strong regional differences in the excess of critical loads occurred in Europe. Whereas in most parts of Greece, southern Italy, France, Spain, Portugal, Ireland and Russia acid deposition was below the critical loads, excess deposition over these no-damage thresholds was a widespread phenomenon in many parts of Germany, Poland and the Czech Republic. In the latter countries more than 90% of the ecosystems were unprotected. A summary of the situation is provided in Table 3, giving both the shares of ecosystems in each region as well as the absolute size of unprotected ecosystems (in hectares). In Europe, about 83 million hectares of ecosystems (i.e. 15% of the total ecosystems area) were not protected against acidification.

In a similar way as for NO_x, the effects of current legislation on emission levels were also calculated for other pollutants contributing to acidification. The emissions of SO_2 are likely to decrease by 60% and the emissions of ammonia by 16%. These reductions are expected to bring significant improvements to ecosystem's protection (Table 3). Looking at acidification, by

Table 3
Ecosystems with acid deposition above their critical loads for acidification in the year 1990 and in the CLE scenario in the year 2010

Country group	1990		CLE	
	1000 ha	%	1000 ha	%
EU + EFTA	42 183	25.1	13 573	8.1
CEE, of which:	40 745	10.3	7419	1.9
Accession countries	11 798	39.2	2889	9.6
Russia	27 485	8.0	4369	1.3
Total Europe	82 928	14.8	20 992	3.7

the year 2010 unprotected ecosystems in Europe shrink from 83 million hectares to 21 million hectares, i.e. to less than 4% of the European ecosystem area. In the Czech Republic and in Poland protection against acidification increases from 10% to more than 70%. Also, in the countries of Western Europe (EU + EFTA) the fraction of unprotected ecosystems declines from 25 to 8%, however still leaving almost 14 million hectares with sulfur and nitrogen deposition above their critical loads.

4.3. *Impacts on ground-level ozone*

The RAINS model estimates that as a result of current legislation NO_x emissions will decline by 38% and VOC emissions by 26% by the year 2010. Using the meteorological conditions of the year 1990, these emission reductions are also expected to lead to a significant decline in ground-level ozone. Fig. 3 displays the decline in ozone exposure between 1990 and 2010, expressed in terms of the AOT40, relevant for natural vegetation. For Western Europe, where in 1990 the highest excess of the AOT40 measure was observed, a decline of 15 to 40% can be expected. In Central Europe (Germany, Poland and Czech Republic) the AOT40 indicator also decreases by 20 to 40%. In Eastern Europe the improvement is much lower (less than 20%), though starting from a lower level in 1990. The impact of the CLE emission reductions on AOT60 is stronger than the one on AOT40.

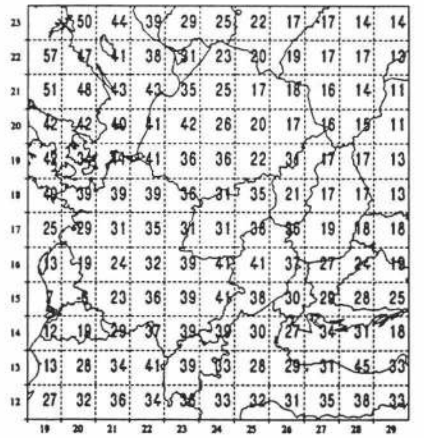

Fig. 3. Percentage reduction in AOT40 in the CLE scenario compared with 1990 level.

5. Optimization

The optimization mode of integrated assessment models can be a powerful tool in the search for cost-effective solutions to combat an air pollution problem. In the RAINS-acidification model, optimization techniques have been used to identify the cost-minimal allocation of resources in order to reduce the gap between current sulfur deposition and the ultimate targets of full critical loads achievement.

In the case of tropospheric ozone, a systematic search for cost-effectiveness appears even more attractive. The facts that several pollutants (NO_x and VOC emissions) are involved, and that important non-linearities between precursor emissions and ozone levels have been recognized, reduce the likelihood of 'intuitive' solutions being identified in the scenario analysis mode.

For simple cost-minimization, the optimization problem can be formulated as

$$\sum_{i=1}^{N} Ci -> \min$$

subject to the set of 'soft' targets with a violation term y:

$$AOT_{lj} - y_{lj} \leq AOT_{lj}^{\max}$$

The country cost curves $c_i(n_i, v_i)$ are constructed from the sectoral cost curves $c_{is}(e_{is})$. Emissions e_i of NO_x and VOC emitters are further subdivided into sectors s to which a set of abatement measures can be applied. In such a case emitters that belong to a particular sector emit either NO_x or VOC or a linear combination of them.

$$c_i(n_i, v_i) = \min \sum_{s=1}^{S} c_{is}(e_{is})$$

constrained to

$$n_i = \sum_{s=1}^{S} n_{is}$$

$$v_i = \sum_{s=1}^{S} v_{is}$$

where:

e_{is}... sectoral emissions

$$s = 1, NO_x \text{ only}, n_{i1} = e_{i1}, v_{i1} = 0$$

$$s = 2, \text{VOC only}, n_{i2} = 0, v_{i2} = e_{i2}$$

$$\text{for } s > 2, n_{is} = e_{is}, v_{is} = \mu_{is} + \beta_{is} e_{is}$$

For each of the pollutants (NO_x, VOC), sectors and countries, such piece-wise linear curves can be used as input to the optimization according to the equation above. Although the solver software used for this exercise is capable of dealing with piece-wise linear constraints, for reasons of increased numerical stability a smoothed approximation of the cost curves has been developed and used. For this the original piece-wise linear information was smoothed at corners.

One may choose to allow violations of the targets AOT^{max}. Violations y of targets are constrained by corresponding lower and upper limits specified for each target type and for each grid:

$$y_{lj}^{min} \leq y_{lj} \leq y_{lj}^{max}$$

A grid is only allowed to violate the target if another grid j in the same country i is compensating for this violation. Therefore, violations of targets have to be balanced (over receptors belonging to the ith country) with over-achievements of targets:

$$\sum_{l=1}^{L} \sum_{j=1}^{J} wo_{ijl} y_{lj} \leq 0$$

with wo_{ijl} as the population or ecosystem densities in the grid.

6. Interim targets for health-related ozone exposure

One possible rationale for selecting environmental interim targets is to establish one common target value to be attained throughout Europe. For practical reasons, this value must be set at a high enough level to be achievable everywhere. In the European context this means that this value will necessarily be above the current exposure in many other regions in Europe. Strategies for achieving this goal will focus emission reductions on the sources contributing to the highest excess, and will not per se imply further actions to improve areas with lower exceedances of the long-term target. As a logical outcome of this approach, the distribution of abatement costs will be largely proportional to the severity of the ozone problem.

An important aspect is the fact that ozone concentrations are not only determined by the surrounding emissions, but are also strongly influenced by the meteorological conditions. While keeping the emissions constant, the AOT60 maxima occur in different regions in different meteorological years. The implications of the inter-annual meteorological variability on the optimized allocation of emission reductions were a major theme of a recent study for the EU (Amann et al., 1997). Assessing the meteorological variations over five years, it was concluded that:

- for constant emissions, the AOT60 typically varies by a factor of plus/minus two as a result of meteorology;
- optimized reduction requirements for NO_x/VOC emissions of individual countries may differ by up to 40%, depending on the meteorological conditions assumed for the analysis;
- preparing for the worst case is expensive, and
- the worst case/year is not identical over all of Europe.

As a consequence, a methodology was developed to simultaneously optimize emission reductions for the meteorological conditions of multiple years. In this study, for each grid cell separately, the meteorological conditions of the year in which the environmental target is most difficult to achieve were ignored, thus aiming at a strategy which would attain the (interim) targets in all of the remaining four years.

As an alternative concept for moving towards the environmental long-term target, a strategy could aim at environmental improvements everywhere where the ultimate targets are not yet achieved, without allowing progress to be limited by the situation at the most difficult areas. A practical example is the 'gap closure' concept, which calls for equal relative improvements of the excess exposure, starting from the situation in a base year. In the international context, this principle has been applied before for the negotiations on the Second Sulfur Protocol of the Convention on Long-range Transboundary Air Pollution and for the EU Acidification Strategy.

As shown in Amann et al. (1997), the optimal allocation of emission controls may be strongly influenced by the need to exactly meet specified targets at a few single grid cells, while for the majority of grid cells the targets are usually over-achieved. The sensitivity of the optimization results to modifications of the environmental targets of these 'binding grids' was the subject of numerous discussions in the past. It was argued that the requirement to achieve stringent isolated targets could possibly imply unbalanced high costs without yielding adequate benefits. This concern is even more pronounced when the targets are not related to absolute levels of exposure or damage, but to some interim targets on the way towards the ultimate environmental objective.

In practice, the 'gap closure' optimization with compensation proceeds along the following steps:

- For each grid cell, a 'soft' target is determined. This soft target is either the AOT60 of the base year (1990) reduced by *x*% (for a *x*% gap closure) or the AOT60 resulting from the CLE scenario, whichever is lower.

- The AOT60 after the optimization may exceed the soft target in a grid, if the excess AOT60 (weighted by the population in the grid) is fully compensated by over-achievements of the soft targets at other grids in the same country (again population-weighted).
- For the AOT60, the country balances (of the excess population exposure indices) extend not only over all grids of a country, but also over all five meteorological years. This means (a) that for the gap closure approach the worst meteorological year is also considered in the optimization, and (b) that excess in some years may be compensated by additional improvements in other years.

7. Results of a combination of the AOT60 ceiling and gap closure targets

Here an attempt is made to combine these two target setting principles (uniform exposure limit and gap closure approach) into one single optimization problem. It is expected that this combination would merge the advantages of both approaches, i.e. put higher pressure on heavily polluted areas while also keeping a certain momentum towards the environmental long-term target in regions where the problem is less severe.

Table 4 provides results on emissions and costs (on top of CLE) of the combined scenario for the EU countries. It must be mentioned that the particular example is just used for illustrative purposes, and by no means should it be interpreted as a practical proposal for actual policy. Costs are highest in Germany, France, Italy, the UK and Belgium, and measures are distributed over most countries. The scenario results in a further decline of NO_x emissions of 52 percentage points below 1990, and of 58 percentage points for VOC. Highest relative NO_x reductions emerge for Belgium and France (− 64 and − 63%, respectively). For Portugal, Ireland, Italy and Spain, further cuts in NO_x than CLE should be implemented. Most stringent VOC measures are required for Belgium, Germany and the Netherlands (− 69%), while a large group of countries (Denmark, France, Greece, Italy, Spain and UK) end up with VOC reductions only a little bit more then CLE.

Table 4
Emissions and control costs of the combined AOT60 3.0 ppm h ceiling/60% gap closure scenario. Percentage changes relate to the year 1990

	NO_x emissions		VOC emissions		Costs above the CLE scenario 10^6
	kt	Change	kt	Change	ECU/yr
Austria	115	− 51%	305	− 29%	0
Belgium	129	− 64%	105	− 69%	605
Denmark	128	− 53%	79	− 52%	23
Finland	155	− 44%	108	− 48%	0
France	592	− 63%	938	− 56%	1118
Germany	1224	− 54%	975	− 69%	1384
Greece	322	− 18%	177	− 41%	183
Ireland	57	− 47%	46	− 59%	4
Italy	960	− 52%	837	− 55%	725
Luxembourg	10	− 52%	8	− 56%	0
Netherlands	270	− 50%	149	− 69%	217
Portugal	114	− 45%	124	− 43%	483
Spain	682	− 41%	615	− 42%	411
Sweden	219	− 36%	287	− 34%	1
UK	1163	− 56%	919	− 65%	722
EU-15	6140	− 52%	5672	− 58%	5877

Figs. 4 and 5 illustrate for the CLE and optimized emission the (rural) AOT60 for the 2nd worst year (out of five meteorological years). The highest AOT60 of more than 4 ppm h occurs in northern France, Belgium and Germany. In the optimized emission scenario these AOT60 values are reduced below the target value of 3.

8. Conclusions

Integrated assessment models offer a tool for developing continental strategies for air pollution control. Such models are able to evaluate alternative options and strategies for reducing emissions taking into account

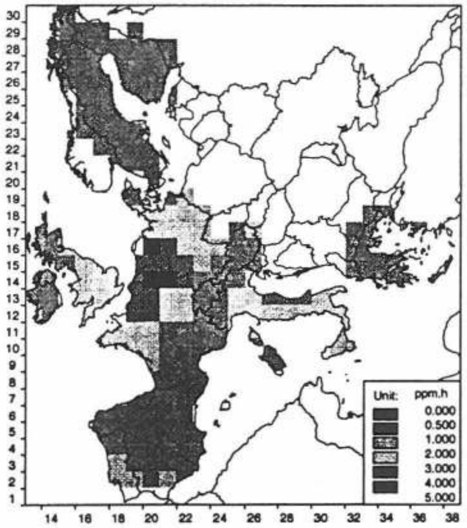

Fig. 4. AOT60 for the CLE scenario ignoring for each grid cell the worst year of five.

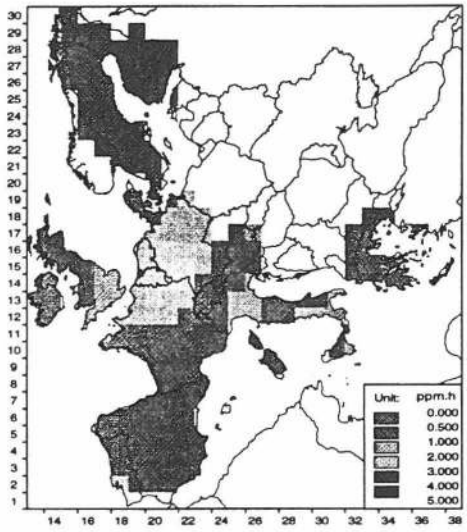

Fig. 5. AOT60 for the optimized scenario ignoring for each grid cell the worst year of five (1989–95).

their costs and environmental impacts, building upon the concept of critical loads and critical levels. In particular, model tools and databases are available to address acidification and eutrophication as well as the threat of tropospheric ozone to vegetation and human health.

Analysis using integrated assessment models reveals major exceedances of critical loads for acidification and critical levels for ozone in large parts in Europe under the present situation. Consequently, it must be concluded that many ecosystems are not sufficiently protected against damage. In spite of substantial improvement brought about by the implementation of current policies, based on present knowledge further controls are necessary to achieve sustainable conditions. The IIASA RAINS model can identify cost-effective, multi-pollutant, multi-effect emission control strategies for this purpose.

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