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From Economic Activities to Ecosystem Protection in Europe

An Uncertainty Analysis of Two Scenarios of the RAINS Integrated Assessment Model

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Foreword

This is a joint report from the EMEP Center for Integrated Assessment Modelling at IIASA, Laxenburg, Austria, and the Coordination Center for Effects under the UN/ECE Working Group on Effects, hosted by the RIVM, Bilthoven, Netherlands.

Earlier drafts of elements of this report were discussed at the 26th Meeting of the Task Force on Integrated Assessment Modelling (May 14-16, 2001, Brussels) and the CCE Workshop in Bilthoven (April 24-27, 2001). Both meetings recognized the proper treatment of uncertainties as a priority area for further scientific work under the Convention on Long-range Transboundary Air Pollution. To this end, a discussion forum on the Internet was installed at the RAINS web site (http://www.iiasa.ac.at/~rains/cgi-bin/forum.pl) to facilitate a targeted discussion process about various aspects of uncertainty treatment.

Acknowledgments

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1 Introduction

In recent international negotiations integrated assessment models were used to quantify reductions of a range of pollutants required to meet politically established targets of environmental quality, e.g., in terms of acidification of ecosystems (e.g., Amann and Lutz, 2000). Without doubt considerable uncertainties exist in almost all parts of the integrated assessment frameworks, e.g., in the emission inventories, the estimates of emission control potentials, the atmospheric dispersion calculations and in the estimates of environmental sensitivities. It is also clear that these uncertainties have a direct impact on the amount by which emissions need to be reduced in order to achieve a desired environmental target. A systematic quantification of the sensitivity of the optimization results in relation to the model and data uncertainties is complicated to do and requires substantial time and resources.

This paper analyzes the uncertainties involved in estimating the areas at risk of acidification in Europe. We explore how, as a consequence of uncertainties in the input data, the uncertainty of critical loads excess in Europe changes from 1990 to 2010. Section 2 introduces the Regional Air Pollution Information and Simulation (RAINS) model that is used as the methodological framework for the analysis. Section 3 reviews the different types of uncertainties inherent in performing calculations with the RAINS model and develops a methodology to propagate uncertainties through the entire chain of model calculations. Section 4 applies this methodology to two calculations, specifying uncertainty ranges for a number of model parameters and assessing their implication on model results. Findings are discussed and conclusions are drawn in Section 5.

2 The RAINS Model

The Regional Air Pollution INformation and Simulation (RAINS)-model developed at the International Institute for Applied Systems Analysis (IIASA, Laxenburg, Austria) provides a consistent framework for the analysis of emission reduction strategies, focusing on acidification, eutrophication and tropospheric ozone. RAINS includes modules for emission generation (with databases on current and future economic activities, energy consumption levels, fuel characteristics, etc.), for emission control options and costs, for atmospheric dispersion of pollutants and for environmental sensitivities (i.e., databases on critical loads). In order to create a consistent and comprehensive picture of the options for simultaneously addressing the three environmental problems (acidification, eutrophication and tropospheric ozone), the model considers emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and volatile organic compounds (VOC). A detailed description of the RAINS model can be found in Schöpp *et al.*, 1999. A schematic diagram of the RAINS model is displayed in Figure 2.1.

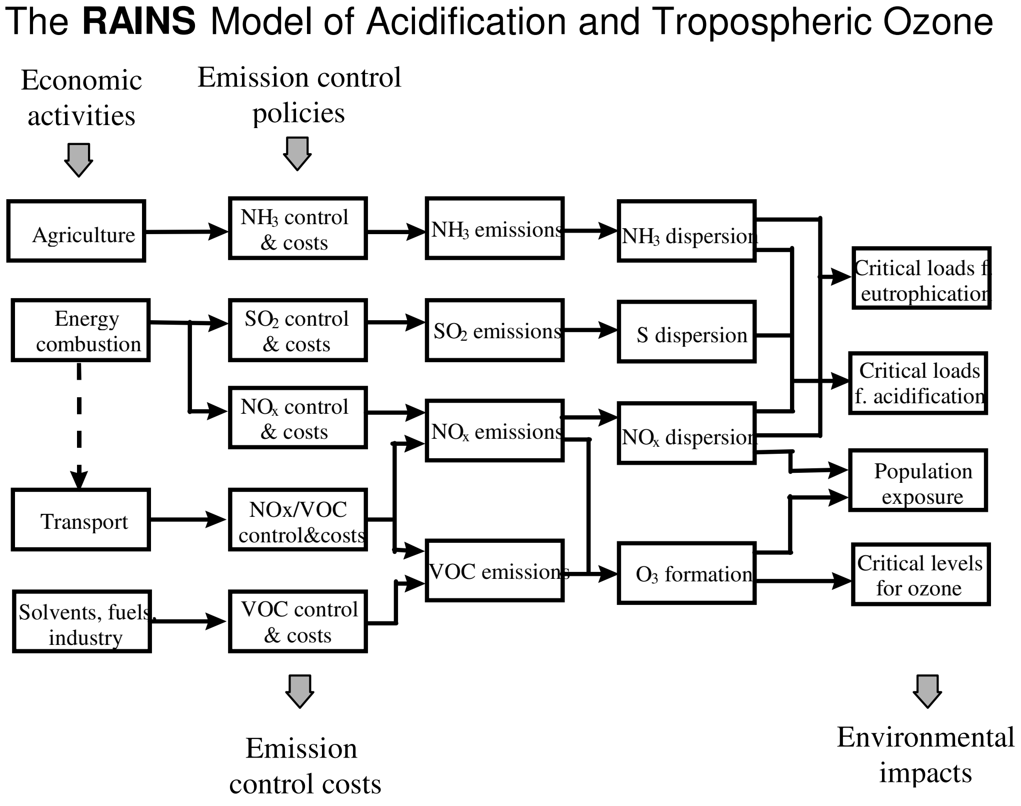


Figure 2.1: Schematic flowchart of the RAINS model framework

The European implementation of the RAINS model incorporates databases on energy consumption for 38 regions in Europe, distinguishing 22 categories of fuel use in six economic sectors. The time horizon extends from the year 1990 up to the year 2010 (Bertok *et al*., 1993). Emissions of SO_2, NO_x, NH_3 and VOC for 1990 are estimated based on information collected by the CORINAIR'90 inventory of the European Environmental Agency and on national information. 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. 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 (Barrett 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, 1992, 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 the Environment (RIVM) in the Netherlands (Posch *et al*., 1999).

The RAINS model can be operated in the ‘scenario analysis’ mode, i.e., following the pathways of the emissions from their sources to their environmental impacts. In this case, the model provides estimates of regional costs and environmental benefits of alternative emission control strategies. Alternatively, an ‘optimization mode’ is available to identify cost-optimal allocations of emission reductions in order to achieve specified air quality targets. This mode of the RAINS model was used extensively during the negotiation process of the Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone of the Convention on Long-range Transboundary Air Pollution and the proposal of the European Commission on a Directive on National Emission Ceilings (Amann and Lutz, 2000).

3 Uncertainties

3.1 Earlier Uncertainty Analysis for the RAINS Model

Like all models, the RAINS model attempts to develop a holistic understanding of a complex reality through a variety of reductionistic steps. This simplification process is burdened with many uncertainties related to methodological issues, lack of understanding and insufficient data.

Several analyses on some aspects of uncertainty have been undertaken during the development and application of the RAINS model:

Sorensen (1994a,b) conducted a sensitivity analysis for the cost calculation routine implemented in the RAINS model and explored how such uncertainties affect the outcome of an optimization analysis. In general, quantitative optimization results were found to be sensitive to variations in the capacity utilization of boilers and in the sulfur contents of fuels. While such variations might change results for individual countries, overall optimized patterns of required emission reductions, however, do not change significantly.

Altman *et al*. (1996) analyzed the influence of uncertainties in emission control costs on calculations of cost-effective European sulfur emission reductions. A specialized solution procedure was developed and a number of different cost curves were generated to model the uncertain costs.

An analysis of the robustness of RAINS-type cost curves (Duerinck, 2000) suggested that uncertainties in the cost components, although relatively high, were much less important for the overall uncertainty than uncertainties in the emissions.

The relationship between deposition targets and the calculated emission ceilings for Denmark has been investigated using Monte Carlo simulation (Bak and Tybirk, 1998). In addition, the sensitivity of the calculated emission ceilings with respect to changes in Danish national data has been analyzed. The analysis explored the sensitivity towards modifications in the energy scenario, the agricultural scenario, the ammonia emission factors and the marginal costs of SO_2, NO_x and ammonia abatement.

Alcamo *et al*. (1987) explored to what extent interregional transport of air pollutants in Europe could be described by linear relations. It was found that the linearity between emissions and deposition strongly depends on the distance between emitter and receptor, the averaging period, the constituent (acidity, oxidants, sulfur, etc.), and the form of deposition (e.g., whether total deposition is considered or wet deposition alone).

The same authors addressed the uncertainty of atmospheric source-receptor relationships for sulfur within Europe (Alcamo and Bartnicki, 1990). Stochastic simulation was used to compute the effect on selected transfer coefficients of uncertainties related to transport wind, meteorological forcing functions, model parameters and the spatial distribution of emissions. Uncertainty estimates for 30 source-receptor combinations – based on one year's meteorological conditions – suggested a relative uncertainty of 10 percent to 30 percent in the transfer coefficients, not correlated with the distance between emission source and receptor. However, their absolute uncertainty (standard deviation) was found strongly correlated with distance and proportional to the values of the transfer coefficients themselves.

Hettelingh (1990) addressed the uncertainty of modeling regional environmental impacts caused by imperfect compatibility of models and available measurement data. He concluded that an uncertainty analysis of integrated environmental models, which integrates different processes (e.g., meteorological, soil and watershed acidification processes) with a probabilistic interpretation of model predictions, might allow different models and data to provide overlapping confidence intervals.

The uncertainty in ecosystem protection levels in Finland was found to be dominated by the uncertainties in critical loads for most parts of the country (Syri *et al.*, 2000).

Van Sluijs (1996) compared different approaches to the management of uncertainties taken by regional integrated assessment models for climate change and regional air quality. A comprehensive treatment of uncertainties turned out to be a challenge for all models available at that time: (i) Models do not fully address all relevant aspects within the whole spectrum of types and sources of uncertainty; (ii) they failed to provide unambiguous comprehensive insight to both the modeler and the user into the quality and limitations of models and their answers and (iii) they failed to address the subjective component in the appraisal of uncertainties.

This finding did not come as a surprise to the developers of integrated assessment models, since it demonstrated that, due to the complexity of such models, an appropriate treatment of uncertainties is far from trivial.

For the particular case of the RAINS model, uncertainty was raised as a matter of concern by industry and countries when the RAINS model was used to guide negotiations under the Convention on Long-range Transboundary Air Pollution on the Gothenburg Protocol and the proposal of the Commission of the European Union on a Directive on National Emission Ceilings. The above studies provide only partial answers, since they addressed uncertainties of individual components of the overall model system.

The computational complexity of the RAINS model system made it difficult to conduct a formal uncertainty analysis with traditional approaches that would yield quantitative insight. For many of the input elements of the model insufficient quantitative information on input data uncertainties is available. Assumptions about error distributions and independence of parameters would be required; and such assumptions would themselves constitute further sources of uncertainty. Instead, the model developers decided to consider uncertainty management as an important guiding principle already during the model development phase and adopted a variety of measures in model design and scenario planning to systematically minimize the potential influence of uncertainties on policy-relevant model output (Schöpp *et al.*, 2001). For instance, at all phases of model development and use, explicit confidence intervals (for emission control potentials, deposition ranges, ozone levels, ecosystems sensitivities, etc.) defined the range within the model was proven to work with sufficient accuracy. Potential reliance of optimized solutions on single point estimates were avoided through integral measures for environmental sensitivities. Specially designed compensation mechanisms allowed controlled violation of environmental targets for single ecosystems with potentially uncertain sensitivities. Wherever possible, preference was given to relative model outcomes (comparing two model outputs) rather than to absolute values. For ground-level ozone, less weight was given to extreme meteorological situations because their representativeness was questionable and the performance of the meteorological model for such rare situations was less certain. Sensitivity analysis attempted to identify systematic biases and showed that with large probability the emission reductions resulting from the model calculations could be considered as minimum requirements, suggesting that there is only little chance that policy measures suggested by the model needed to be revised in the future in the light of new information.

3.2 A Taxonomy of Uncertainties in the RAINS Model

To help make the assembling of uncertainties more systematic, we propose the following taxonomy, which classifies uncertainties in terms of model characteristics (after Alcamo and Bartnicki, 1987):

- Model structure – these are uncertainties resulting from the specified collection of model terms and how they are related, containing all physical assumptions of the model;

- parameters – uncertainties from coefficients which are constant in time or space;
- forcing functions – uncertainties from coefficients which inherently change in time and space;
- initial state – uncertainties inherent in boundary and initial conditions.

Table 3.1 lists examples of these types of uncertainties, distinguishing the three major components of the RAINS model (emission calculation, atmospheric dispersion, critical loads).

Table 3.1: Taxonomy of uncertainties in the RAINS model

Model structure	Emission calculations	Selected sectoral aggregation
		Determination of mean values
	Atmospheric dispersion	Linearity in atmospheric dispersion
		Selected spatial resolution, ignoring in-grid variability
		Country size (country-to-grid)
	Critical loads estimates	The threshold concept, e.g., the critical Ca/Al ratio
		Selected aggregation of ecosystems
		Static representation of a dynamic process
Parameters	Emission calculations	Expected values for fuel quality, removal efficiencies and application rates
	Atmospheric dispersion	Expected values of parameters for describing chemical and physical processes (conversion rates, deposition rates)
		Mean transfer coefficient in view of inter-annual meteorological variability
	Critical loads estimates	Expected values of base cation deposition and uptake, throughflow, nitrogen uptake in critical loads calculations
Forcing functions	Emission calculations	Accuracy of statistical information on economic activities
		Projections of sectoral economic activities
		Future implementation of emission controls
	Atmospheric dispersion	Spatial distribution of emissions within countries
		Accuracy of meteorological data
Initial state	Emission calculations	Uncontrolled emission factors
		State of emission controls in the base year
	Atmospheric dispersion	Natural emissions
		Hemispheric background

3.3 A Methodology for Assessing Uncertainties

We propose a methodology to address the uncertainties in the various model terms (variables and parameters) and to explore how they propagate through the entire model chain (Figure 3.1) and thereby influence the uncertainty of intermediate model output, such as national emissions, deposition fields and critical load excess.

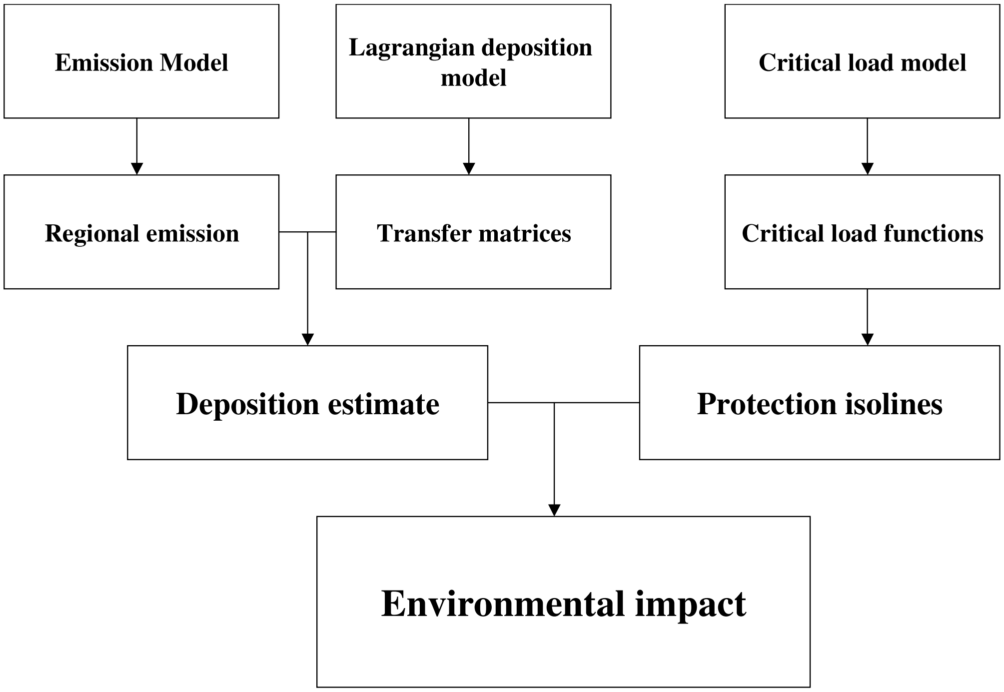


Figure 3.1: Flowchart of the uncertainty analysis for ecosystems protection. Uncertainty ranges are specified for the input parameters in the emissions, deposition and critical loads models, as well as estimating the errors from the model integration.

3.3.1 Definition

Here we consider a deterministic model term *A* (either a model variable or parameter), whose uncertainty is represented by an uncertainty factor χ with the expected value of one and the standard deviation σ_χ, so that the uncertain model term is defined as A_χ. Thereby the coefficient of variation of the uncertain term A_χ is σ_χ:

$$CV_{A\chi} = \frac{\sigma_{A\chi}}{A} = \frac{A\sigma_\chi}{A} = \sigma_\chi \qquad \text{(Equation 1)}$$

3.3.2 Terminology

In the remainder of the paper we denote uncertain terms by Greek characters, while deterministic terms are printed in Latin. Dependent uncertain terms are marked with $\overline{\overline{X}}$; expected values of $\overline{\overline{X}}$ are marked as $\overline{X}$. Furthermore, we denote the following statistical operators:

E[ ]	expected value
Var[ ]	variance of a value
Cov[,]	covariance of two values

3.3.3 The Basic Concept

To explore the influence of the uncertainties of individual model terms on overall model results, we have developed an analytical method to propagate the errors presented as coefficients of variation through the entire model chain. We assigned to a number of model terms uncertainty factors χ and attempted to quantify them based on available statistics and expert judgment. We determine the resulting uncertainty for the major intermediate outputs of the RAINS model, i.e., for national emissions of acidifying substances, for deposition of sulfur and nitrogen compounds and for excess deposition over critical load. Finally, using standard statistical operations we quantified the influence of these uncertainties through the entire calculation chain from emissions to ecosystems protection.

3.4 Uncertainty of Calculated Emissions

For the deterministic case the RAINS model calculates for a given economic sector *j* in country *i* the emissions $em_{x,i}$ of a certain substance *x* as the product of a rate of economic activity $ac_{x,i,j}$ the uncontrolled emission factor $ef_{x,i,j}$ (representing theoretical emissions in absence of any emission control measures), the application rates $af_{x,i,j,k}$ and removal efficiencies $rem_{x,i,j,k}$ of the available emission control options *k*:

$$em_{x,i} = \sum_{j} act_{x,i,j} ef_{x,i,j} (1 - \sum_{k} af_{x,i,j,k} rem_{x,i,j,k}) \qquad \text{(Equation 2)}$$

Details about emission calculations are provided in Cofala and Syri (1998a,b) and Klimont *et al.* (2000).

While this calculation formula bears uncertainties in itself (especially in cases where legally binding emission limit values are in force), all of the above mentioned model parameters are associated with uncertainties. Let's define for each of the model terms the expected value and an uncertainty factor:

act = the expected activity level

α = uncertainty factor for the activity level

ef = expected uncontrolled emission factor per unit of activity

ε = uncertainty factor for the emission factor

af = expected application rate for the abatement technology

γ = uncertainty factor for the application rate

rem = expected removal efficiency of the abatement technology

η= uncertainty factor for removal efficiency

With these definitions, the uncertain emissions $\overline{\overline{em}}$ for pollutant *x* and country *i* are calculated as

$$\overline{\overline{em}}_{x,i} = \sum_j act_{x,i,j}\alpha_{x,i,j}ef_{x,i,j}\varepsilon_{x,i,j}(1-\sum_k af_{x,i,j,k}\gamma_{x,i,j,k}rem_{x,i,j,k}\eta_{x,i,j,k}) \cdot$$

(Equation 3)

If we assume that no correlations exist between the uncertainty factors for the activity levels (α), the emission factors (ε), the application rates (γ), and the removal efficiencies (η), then the expected emissions $\overline{em}_{x,i}$ emerge from Equation 3 as

$$\overline{em}_{x,i} = \sum_j act_{x,i,j}ef_{x,i,j}(1-\sum_k af_{x,i,j,k}rem_{x,i,j,k}), \qquad \text{(Equation 4)}$$

which is equal to the deterministic case (Equation 2).

However, certain variables and model parameters are common input for calculations for different pollutants *(x,y)*, regions *(i,p)* and sectors *(j,q)* (e.g., activity rates, removal efficiencies of emission control options, etc.). Therefore, there exists a covariance between the emission estimates of different regions and of different pollutants:

$$\begin{aligned}Cov[\overline{\overline{em}}_{x,i}, \overline{\overline{em}}_{y,p}] = &\sum_j\sum_q (act_{x,i,j}act_{y,p,q}ef_{x,i,j}ef_{y,p,q}\mathrm{E}[\alpha_{x,i,j}\alpha_{y,p,q}]\mathrm{E}[\varepsilon_{x,i,j}\varepsilon_{y,p,q}]\\ &(\sum_k\sum_m af_{x,i,j,k}af_{y,p,q,m}rem_{x,i,j,k}rem_{y,p,q,m}\mathrm{E}[\gamma_{x,i,j,k}\gamma_{y,p,q,m}]\mathrm{E}[\eta_{x,i,j,k}\eta_{y,p,q,m}]\\ &-\sum_k af_{x,i,j,k}rem_{x,i,j,k} - \sum_m af_{y,p,q,m}rem_{y,p,q,m} + 1)) - \overline{em}_{x,i}\overline{em}_{y,p}\end{aligned}$$

(Equation 5)

The expected value of a product is defined according to Equation 7 of the Annex.

For further analysis the variances of national emissions are also of interest. The variance of emissions of pollutant *x* at region *i* is the covariance of emission *x* itself

$$Var[\overline{\overline{em}}_{x,i}] = Cov[\overline{\overline{em}}_{x,i}, \overline{\overline{em}}_{x,i}] \qquad \text{(Equation 6)}$$

3.5 Uncertainty of Calculated Deposition

The deterministic RAINS calculations determine deposition of pollutant *x* at a given receptor site *e* by multiplying the emissions $em_{x,i}$ of all countries *i* with transfer (dispersion) coefficients for wet and dry deposition ($w_{x,i,e}$, $d_{x,i,e}$), respectively:

$$dep_{x,e} = \sum_i em_{x,i}(w_{x,i,e} + d_{x,i,e}) \qquad \text{(Equation 7)}$$

For the uncertainty analysis we associate each of the deterministic terms with an uncertainty factor:

$\xi_{x,i}$ = emission uncertainty factor for compound *x* and region *i,*

$w_{x,i,e}$ = wet deposition transfer coefficient for compound *x* from region *i* to receptor site *e*

$\omega_{x,i,e}$ = uncertainty factor for the wet deposition transfer coefficient

$d_{x,i,e}$ = dry deposition transfer coefficient for compound *x* from region *i* to receptor site *e*

$\delta_{x,i,e}$ = uncertainty factor for the wet deposition transfer coefficient

With these uncertainty terms we calculate deposition as

$$\overline{\overline{dep}}_{x,e} = \sum_i \overline{em}_{x,i}\xi_{x,i}(w_{x,i,e}\omega_{x,i,e} + d_{x,i,e}\delta_{x,i,e}) . \qquad \text{(Equation 8)}$$

Because the uncertainty factors in Equation 8 have expected values of one, the expected deposition $\overline{dep}$ is

$$\overline{dep}_{x,e} = \sum_i \overline{em}_{x,i}(w_{x,i,e} + d_{x,i,e}) . \qquad \text{(Equation 9)}$$

Assuming the uncertainties in emissions (ξ) are uncorrelated with the uncertainties of the transfer coefficients (ω, δ), the covariance between compounds *x* and *y* in grid *e* is

$$\begin{aligned} Cov[\overline{\overline{dep}}_{x,e}, \overline{\overline{dep}}_{y,e}] = \sum_i \sum_p (\overline{em}_{x,i}\overline{em}_{y,p}\mathrm{E}[\xi_{x,i}\xi_{y,p}](w_{x,i,e}w_{y,p,e}\mathrm{E}[\omega_{x,i,e}\omega_{y,p,e}] \\ + d_{x,i,e}d_{y,p,e}\mathrm{E}[\delta_{x,i,e}\delta_{y,p,e}] + w_{x,i,e}d_{y,p,e}\mathrm{E}[\omega_{x,i,e}\delta_{y,p,e}] \\ + w_{y,p,e}d_{x,i,e}\mathrm{E}[\omega_{y,p,e}\delta_{x,i,e}])) - \overline{dep}_{x,e}\overline{dep}_{y,e} \end{aligned}$$

(Equation 10)

As for emission calculations, the variance of deposition of pollutant *x* at the receptor site *e* is the covariance of deposition of the compound *x* itself:

$$\sigma^2_{x,e} = Var[\overline{\overline{dep}}_{x,e}] = Cov[\overline{\overline{dep}}_{x,e}, \overline{\overline{dep}}_{x,e}] \qquad \text{(Equation 11)}$$

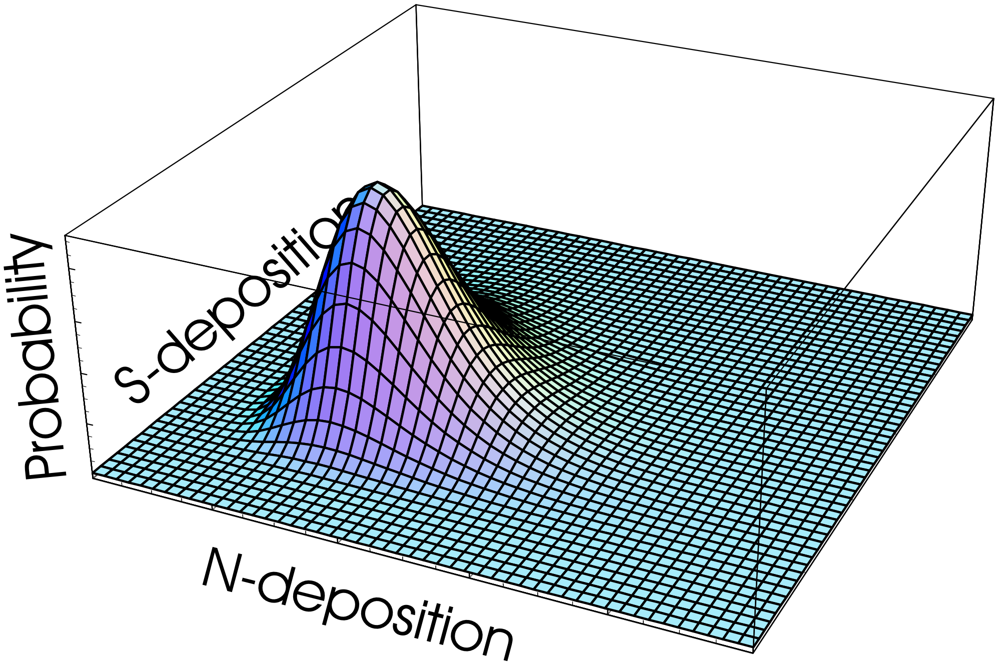


Figure 3.2: Probability density of sulfur and nitrogen deposition

For comparing acid deposition with critical loads protection isolines, we need to combine deposition of oxidized and nitrogen compounds originating from NO_x and NH_3 emissions (Figure 3.2). The expected total nitrogen deposition is calculated as

$$\overline{dep}_{N,e} = \overline{dep}_{NOx,e} + \overline{dep}_{NHy,e} \qquad \text{(Equation 12)}$$

The variance of total nitrogen deposition is then the sum of the variances of the oxidized and reduced nitrogen depositions and their covariance:

$$\sigma^2_{N,e} = \sigma^2_{NOx,e} + \sigma^2_{NHx,e} + 2\sigma_{NOx,e}\sigma_{NHx,e}\rho_{NOx.NHx,e}\,. \qquad \text{(Equation 13)}$$

The correlations ρ are derived from the covariances according to Equation 10.

The correlation between the deposition of sulfur and total nitrogen is obtained as

$$\rho_{SOx.N,e} = \rho_{SOx.NOx,e}\frac{\sigma_{NOx,e}}{\sigma_{N,e}} + \rho_{SOx.NHx,e}\frac{\sigma_{NHx,e}}{\sigma_{N,e}}\ . \qquad \text{(Equation 14)}$$

3.6 Uncertainty of Ecosystem Protection

The RAINS model calculates acid deposition $dep_{x,e}$ from the emissions $em_{x,i}$ and compares it with the critical loads for the ecosystems.

Deposition of nitrogen and sulfur compounds is computed as single values for each grid cell. Within a single EMEP grid cell, however, many (up to 100,000 in some cases) critical loads for various ecosystems, mostly forest soils and surface waters, have been calculated. These critical loads are sorted according to their magnitude taking into account the area of the ecosystem they represent, and the so-called cumulative distribution function is constructed. This cumulative distribution function is then compared to the single deposition values for that grid cell.

In practical terms, the RAINS model uses so-called ‘protection isolines’ for each grid cell describing pairs of sulfur and nitrogen deposition that protect an equal area of ecosystems. Such protection isolines are constructed by calculating protection points along rays passing through origin of the sulfur-nitrogen plane.

While the calculated deposition of sulfur and nitrogen compounds is associated with uncertainties, the protection isolines themselves also bear significant uncertainties related to the concept of establishing critical chemical thresholds, the methodology used to determine them, the underlying data, etc.

We define the uncertainties of the points of protection isolines along the rays through the origin of the sulfur/nitrogen plane (Figure 3.3), so that the probability P_n of a certain percentage of the ecosystems being protected at given deposition x is also defined along rays from the origin. The probability (Figure 3.4) is calculated for a fixed sulfur to nitrogen ratio as

$$P_n\left(r(x) < r(pi_n(x))\right) = 1 - G_n\left(x, r(x)\right) \qquad \text{(Equation 15)}$$

where

$r(x)$	the distance of the point x (denoting a pair of sulfur and nitrogen deposition) from the origin (in equivalents/hectare/year), calculated as $r(x) = \sqrt{\Delta S(x)^2 + \Delta N(x)^2}$
$r(pi_n(x))$	the distance of the isoline for protection percentage n from the origin for the sulfur/nitrogen ratio of point x
$G_n(x,r(x))$	the value of the cumulative distribution function of the protection isoline for protection percentage n having the same S/N ratio as the point x at the distance $r(x)$. For each S/N ratio the distribution is defined by the expected value of the distance between the isoline and the origin and the standard deviation for the same S/N ratio.

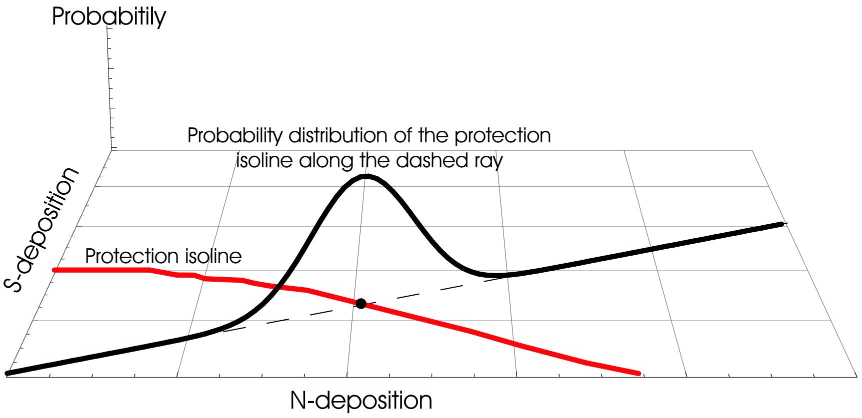


Figure 3.3: Probability density of a selected protection isoline along an arbitrary ray

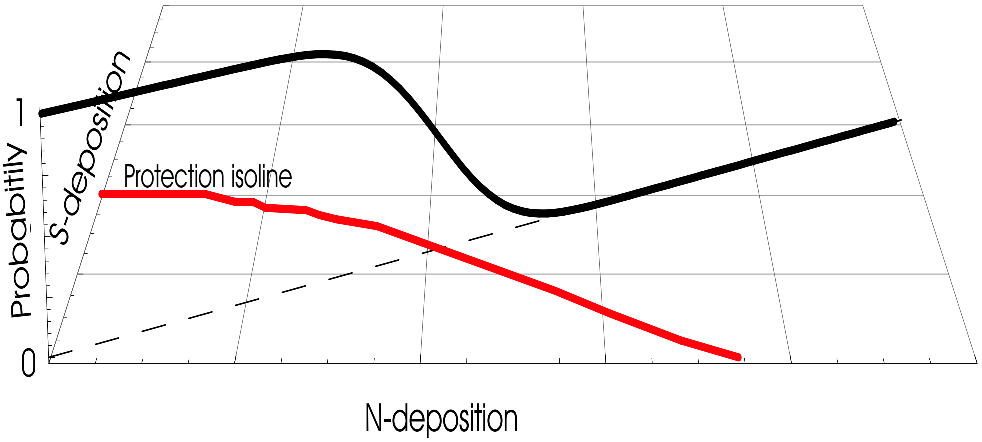


Figure 3.4: Protection probability along an arbitrary ray

Evaluated for all sulfur/nitrogen ratios we obtain a protection probability surface as illustrated in Figure 3.5.

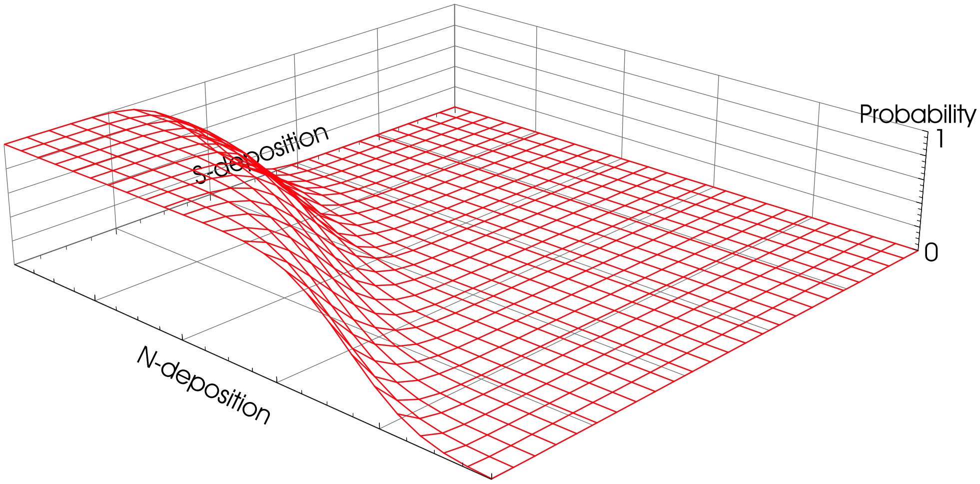


Figure 3.5: Protection probability surface for a given protection percentile

The uncertainties of deposition and of protection isolines can be combined, so that the probability to protect with a given deposition (D_N,D_S) n percent of ecosystems is calculated as:

$$P_n \Big|_{f_D} = \int_0^\infty \int_0^\infty P_n\big(r(D_{N,}D_S) < r(pi_n(D_{N,}D_S))\big)\, f_D\big(D_{N,}D_S\big)\ \mathbf{d}D_S\mathbf{d}D_N \qquad \text{(Equation 16)}$$

with f_D as the bivariate distribution of deposition.

4 Uncertainties in the RAINS Calculations of Ecosystems Protection

As a practical example, it was analyzed how uncertainties in important model terms propagate through the calculation chain of the RAINS model, i.e., from emissions over atmospheric dispersion to environmental impacts. For each of the elements, critical model terms were selected. An attempt was made to quantify the uncertainties of these model terms based on expert judgment.

The general concept of the analysis is outlined in Figure 3.1.

4.1 Uncertainties in Emission Estimates

The methodology adopted by the RAINS model to estimate emissions is associated with a variety of different types of uncertainties. Following the taxonomy introduced above, uncertainties are caused by the structure of the RAINS model. For instance, the selected aggregation level might influence calculation results, i.e., how emission sources are aggregated into certain economic sectors and categories of fuels. Uncertainties are also related to the need to determine mean values for a RAINS category that in reality encompasses an inhomogeneous range of emission sources. The determination of the expected values for fuel quality, emission control efficiencies and application rates of emission control measures causes important parameter uncertainties. For the forcing functions, uncertainty is an issue for the accuracy of statistical information on economic activities as well as for the projection of future activity rates. Depending on the operation mode of the RAINS model, the implementation of emission control measures (or compliance with legislation) could also be a major source of uncertainties. Uncertainties related to the initial state of the models are caused by estimates of the hypothetical uncontrolled emissions and the implementation of emission control measures in the base year.

Table 4.1: Sources of uncertainties for the emission calculations in the RAINS model

Model structure	Selected sectoral aggregation Determination of mean values
Parameters	Expected values for fuel quality, removal efficiencies and application rates
Forcing functions	Accuracy of statistical information on economic activities Projections of sectoral economic activities Future implementation of emission controls
Initial state	Uncontrolled emission factors State of emission controls in the base year

4.1.1 Assumed Uncertainties in Input Data for SO_2 and NO_x

An attempt was made to quantify the uncertainties of some of the key model terms. Based on expert judgment, coefficients of variation (CV) were compiled for

- activity rates (*act*); in this case different uncertainties were specified for the base year 1990 and for the values projected for 2010,
- uncontrolled emission factors (*ef*) (mean values for a source category),
- efficiencies (rem) of the various emission control measures considered in the RAINS model, and
- the rates of application (*af*) of such measures.

For quantifying the uncertainties, four groups of countries are distinguished (Table 4.2):

- The best data quality is assumed for EU-15 and EFTA countries (Norway, Switzerland), for which harmonized and quality controlled international statistics are available.
- The second group of countries includes the 'first wave' EU accession countries with a fairly advanced economic and administrational reform (the Czech Republic, Estonia, Hungary, Poland, Slovakia, Slovenia).
- All other countries are included in the third group.
- Little solid information is available for international sea traffic.

Uncertainties in Activity Data

Uncertainties in activity data originate from

- inaccuracies in measuring physical quantities of consumed fuels or manufactured products,
- errors and biases in measuring the heat content of fuels,
- possible international inconsistencies in fuel- and sector definitions of national statistics,
- the assumptions about future economic development and structural changes in energy systems, etc.

Although the RAINS database uses to the maximum possible extent internationally harmonized data sets with coherent definitions and compilation methods, reporting practices of countries are not always fully consistent. For instance, national statistics of different countries classify heating oil of a similar quality either as "heavy fuel oil" or as "light fuel oil". Also fuel consumption of industrial power plants and municipal heating plants is sometimes reported in the power plant sector, while in other cases it is included in the industrial or domestic sector, depending on the conventions used in individual countries.

For the base year 1990, the economic transition of the former centrally planned economies and the formation of new countries are additional sources of uncertainties, since new statistical systems for new economic agents (private firms) and new administrative units had to be created. Obviously, for such transition countries future projections of economic development are more uncertain than for countries with stable market economies.

Since SO_2 and NO_x calculations are based on the same activity data, errors introduced by this term into SO_2 and NO_x calculations are perfectly correlated.

Table 4.2: Groups of countries/regions for which different assumptions on uncertainties in emission data were made, and the coefficients of variation (CV) for the activity data (sectoral fuel consumption, industrial production)

Group		1990	2010
I	EU-15, Norway and Switzerland	0.06/0.10	0.12/0.18
II	Czech Rep., Estonia, Hungary, Poland, Slovakia, Slovenia	0.09/0.15	0.15/0.22
III	Other countries	0.12/0.18	0.18/0.27
IV	International sea traffic	0.20	0.30

Uncertainties in Emission Factors

Many factors contribute to uncertainties of the uncontrolled emission factors that are used to calculate SO_2 and NO_x emissions in the RAINS model. For instance, the extrapolation of emission factors that were monitored for a few individual sources under certain conditions to entire sectors, different operating conditions and other countries is certainly an important aspect. It is well known that emissions often depend on the age of the equipment and on maintenance, and it is difficult for many reasons to accurately reflect this in emission inventories.

Source-group specific uncertainties in the uncontrolled emission factors are assumed for this analysis (Table 4.3 for SO_2, Table 4.4 for NO_x). For SO_2 emission factors of Group I countries, a CV of 0.05 has been adopted for most sectors. Larger uncertainties are associated with SO_2 and NO_x emissions from brown coal combustion due to the greater variability of fuel quality even from the same coalmine and the limited possibility to stabilize combustion conditions. Higher uncertainties prevail also in the transport sector, where the determination of emission factors that are representative for the entire vehicle fleet, driving conditions and maintenance level is difficult.

To reflect conditions where less effort is spent to determine country-specific emission factors, where lower levels of maintenance prevail or where fast changes in technology are expected, the CVs given in Table 4.3 are increased by 25 percent for Group II and 50 percent for Group III countries. For international sea traffic 50 percent larger CVs are assumed.

Generally higher uncertainties are assumed for NO_x, emission factors.

No correlations between the uncertainties of emission factors of different source categories are assumed.

Table 4.3: Coefficients of variation for uncontrolled SO_2 emission factors for Group I (EU and EFTA) countries. Values for Group II countries are increased by 25 percent, for Group III countries by 50 percent.

	Brown coal	Hard coal	Coke, briquettes	Gas	Heavy fuel oil	Diesel, light fuel oil	Gasoline	Other solids
Refineries, coke prod.	0.10	0.05	0.05	0.05	0.05	0.05	0.05	
Power plants	0.10	0.05	0.05	0.05	0.05	0.05		0.05
Industry	0.10	0.05	0.05	0.05	0.05	0.05		0.05
Domestic	0.10	0.05	0.05	0.05	0.05	0.05		0.05
Transport					0.05	0.05	0.05	
Industrial process emissions	0.10							

Table 4.4: Coefficients of variation for uncontrolled NO_x emission factors for Group I (EU and EFTA) countries. Values for Group II countries are increased by 25 percent, for Group III countries by 50 percent.

	Brown coal	Hard coal	Coke, briquettes	Gas	Heavy fuel oil	Diesel, light fuel oil	Gasoline	Other solids
Refineries, coke prod.	0.15	0.075	0.075	0.075	0.075	0.075	0.075	
Power plants	0.15	0.075	0.075	0.075	0.075	0.075		0.075
Industry	0.15	0.075	0.075	0.075	0.075	0.075		0.075
Domestic	0.15	0.075	0.075	0.075	0.075	0.075		0.075
Road transport					0.075	0.1125	0.1125	
Off-road transport					0.075	0.1125	0.1875	
Industrial process emissions	0.15							

Uncertainties in Removal Efficiencies

Without any doubt there are also significant uncertainties associated with determining mean removal efficiencies of the emission control measures in a country. For instance, design efficiencies might vary over Europe, local fuel quality may influence the performance of emission abatement devices, and plant operators have certain freedom to run their equipment in a more or less efficient way.

For this analysis it is assumed that for a number of reasons uncertainties in the efficiency of technically more advanced techniques are lower than those of simple measures. In many cases advanced techniques (e.g., high efficiency flue gas desulfurization) are applied in plants with continuous monitoring of emissions, where compliance with stringent emission standards is required. Also if standards for fuel quality are very tight (e.g., sulfur content of diesel oil), controls are often more stringent.

Coefficients of variation (CV) for SO_2 and NO_x control technologies are presented in Table 4.5 and Table 4.6. These coefficients are uniform for all countries in Europe.

Table 4.5: Assumed uncertainties of the removal efficiency parameter used in the SO_2 emission calculations (Equation 4). The uncertainty is presented as the coefficient of variation.

Emission control options	Coefficient of variation (CV) for removal efficiency
Low sulfur fuels for stationary sources (coal, coke, heavy fuel oil, gas oil)	0.05
Low sulfur diesel for transport sources	0.005
Limestone injection, fluidized bed combustion	0.04
High efficiency flue gas desulfurization	0.005
Industrial process emissions – Stage 1	0.05
Industrial process emissions – Stage 2	0.035
Industrial process emissions – Stage 3	0.03

Table 4.6: Assumed uncertainties of the removal efficiency parameter used in the NO_x emission calculations (Equation 4). The uncertainty is presented as coefficient of variation.

Emission control options	Coefficient of variation (CV) for removal efficiency
Combustion modification for stationary sources	0.05
SCR/SNCR for stationary sources (also in combination with combustion modification)	0.05
EURO 1 standards for gasoline vehicles	0.075
EURO 2 standards for gasoline vehicles	0.05
EURO 3 standards for gasoline vehicles	0.025
EURO 4 standards for gasoline vehicles	0.015
EURO 1and 2 standards for diesel vehicles	0.075
EURO 3 standards for diesel vehicles	0.05
EURO 4 standards for diesel vehicles	0.025
Control of industrial process emissions – Stage 1	0.10
Control of industrial process emissions – Stage 2	0.075
Control of industrial process emissions – Stage 3	0.05

4.1.2 Assumed Uncertainties in Input Data for NH_3

The calculations of ammonia emissions in the RAINS model follows a slightly different path, since the several phases during which emissions could occur are treated separately. Thereby it is possible to associate differentiated uncertainties to the various stages. To reflect differences in the quality of available information for western European and central and eastern European countries, two groups of countries are considered.

Uncertainties in Activity Data

General uncertainty estimates for animal numbers (i.e., number of dairy cows, fattening pigs, laying hens, et.) and fertilizer use statistics (SAEFL, 2001) are not available. Van der Hoek (1995) suggests that, e.g., for the Netherlands, the uncertainty of animal number statistics is in the range of 10 percent. Obviously uncertainties will increase for future projections. Assumptions for this study are listed in Table 4.7.

Table 4.7: Uncertainties in the activity data for ammonia, coefficients of variation

	EU-15 + EFTA		Other countries	
	1990	2010	1990	2010
Cattle	0.075	0.15	0.10	0.20
Pigs	0.075	0.15	0.10	0.20
Poultry	0.10	0.20	0.15	0.30
Fur animals	0.05	0.10	0.05	0.10
Horses	0.05	0.10	0.10	0.20
Sheep	0.15	0.30	0.15	0.30
Application of other N fertilizers	0.05	0.10	0.10	0.20
Application of urea	0.05	0.10	0.10	0.20
N fertilizer production	0.05	0.10	0.075	0.15
Other industry	0.05	0.10	0.15	0.30
Waste treatment	0.15	0.30	0.30	0.60
Other sources	0.25	0.50	0.50	1.00

Uncertainties in Emission Factors

In general there is good understanding of the processes that cause ammonia emissions, with the possible exception for emissions from solid manure. However, there are still large uncertainties in the determination of the parameters that are needed to derive country specific emission factors. Since actual measurement studies were conducted only in a few countries (mainly in western Europe), brave assumptions have to be made for extrapolating results of such studies to other countries with sometimes rather different conditions.

Van der Hoek (1995) reports a typical uncertainty range of 30 percent for livestock emission factors, not considering the inter-annual meteorological differences that might greatly affect actual ammonia losses from manure management.

Sutton (1995) indicates that for emission factors for fertilizer application the major source of uncertainties is the generalization of emission factors rather than the area of crops under cultivation. Generally he estimates an uncertainty of about 50 percent.

Several measurement campaigns indicated the importance of fertilizer application practice on ammonia losses (e.g., Isherwood, 2001; UN/ECE, 1999), especially for urea fertilizers. However, there is an important lack of detailed information on national practices to handle manure and fertilizers. A coefficient of variation of 40 percent is assumed in this study for the urea emission factor, while for other N-fertilizers the CV is assumed to be 25 percent (Table 4.8). For central and eastern European countries, generally higher uncertainties were assumed (Table 4.9).

Table 4.8: Uncertainties of emission factors used for the calculation of ammonia emissions for western European countries. The uncertainty is presented as coefficient of variation (CV).

	Housing	Storage	Manure application	Grazing	Non animal
Cattle	0.075	0.15	0.20	0.20	
Pigs	0.15	0.20	0.20		
Poultry	0.15	0.15	0.20		
Fur animals	0.25	0.35	0.20	0.25	
Horses	0.25	0.35	0.20	0.25	
Sheep	0.25	0.35	0.20	0.25	
Application of other N fertilizers					0.25
Application of urea					0.40
N fertilizer production					0.15
Other industry					
Waste treatment					
Other sources					

Table 4.9: Uncertainties for emission factors used for the calculation of ammonia emissions for central and eastern European countries. Uncertainty are presented by their coefficients of variation (CV).

Animal category	Housing	Storage	Manure application	Grazing	Non animal
Cattle	0.20	0.30	0.30	0.40	
Pigs	0.20	0.30	0.30		
Poultry	0.20	0.30	0.30		
Fur animals	0.25	0.35	0.30	0.25	
Horses	0.25	0.35	0.30	0.25	
Sheep	0.25	0.35	0.30	0.25	
Application of other N fertilizers					0.25
Application of urea					0.40
N fertilizer production					0.15
Other industry					
Waste treatment					
Other sources					

Uncertainties in the Reduction Efficiencies of Emission Control Techniques

The aggregation of various emission sources into categories for which several emission control options with varying efficiencies are available constitutes an important source of uncertainty when determining the reduction efficiency. Furthermore, it was shown that even the same techniques perform differently depending on several parameters such as soil types, application practice, etc. Several studies explored the ranges of efficiencies for various technologies (UN/ECE, 1999; Webb, 2001). For this study we assume that the uncertainty of reduction efficiencies ranges typically between 20 and 40 percent (Table 4.10). For some techniques, e.g., housing adaptation in Eastern Europe, the uncertainty could reach up to 80 percent owing to poor information on current practices.

Since the RAINS methodology calculates emissions through a chain of different states, correlations between reduction efficiencies at the different stages are important.

Table 4.10: Uncertainty in the removal efficiencies. The uncertainty is presented as the coefficient of variation (CV)

	Covered storage	Low NH_3 manure application	Low nitrogen feed			Grazing	Housing adaptation	
			Housing	Storage	Manure spreading		Housing	Storage
Cattle, liquid manure	0.05	0.10	0.20	0.20	0.20	0.15	0.20	0.05
Cattle, solid manure		0.15	0.20	0.20	0.20	0.15		
Pigs, liquid manure	0.05	0.10	0.20	0.20	0.20	0.15	0.10	0.05
Pigs, solid manure		0.15	0.20	0.20	0.20	0.15		
Laying hens	0.05	0.10	0.20	0.20	0.20	0.15	0.075	0.05
Other poultry	0.05	0.10	0.20	0.20	0.20	0.15	0.075	0.05
Sheep		0.10						

4.1.3 Resulting Uncertainties in Emission Calculations

With the uncertainties of input data as specified in the preceding section and equations 3 and 4, uncertainties of the resulting emission estimates can be derived.

To present uncertainties of calculation results, we provide the standard deviation in absolute terms (kilotons) and the 95 percent confidence interval expressed as a percentage of the expected value. The confidence interval is calculated based on the assumption of a normal distribution of the overall uncertainty. (For normal distribution, the 95 percent confidence interval is roughly twice the standard deviation).

Emission uncertainties are evaluated on a sectoral basis for three countries (UK, Switzerland and Romania). The uncertainties of national total emissions are provided for all countries, and a sensitivity analysis that explores how much the individual factors contribute to the overall uncertainties is presented.

Sectoral Emission Estimates

Uncertainties of sectoral emission estimates are presented for two countries (UK and Switzerland) for 1990 and 2010.

For the UK, the assumptions described in the preceding section lead for the year 1990 to similar uncertainty ranges for the 10 most important source sectors (Table 4.11). An exception is the industrial process emission sector, where the emission factors are associated with larger uncertainties. Since we do not assume correlation between the parameters of different source sectors, errors compensate to a certain extent so that the overall uncertainty in national total emissions is smaller than that of individual sectors.

This situation looks different if we consider the projection for the year 2010 (Table 4.12). While the expected value of emissions declines by 66 percent, uncertainties increase mainly due to three reasons:

- First, we assume that our knowledge about future activity data is less certain than for the past.
- Second, the introduction of emission control devices adds an additional source of uncertainty to the emission estimates (the removal efficiency). For instance, as a consequence of the more uncertain activity data projections and the more stringent emission controls, the relative uncertainty range (the confidence interval) of emissions from coal power plants in the UK will increase from ±16 to ±26 percent. In absolute terms, however, the uncertainty will certainly decline, e.g., the standard deviation from 199 kilotons in 1990 to 49 kilotons in 2010.
- Third, since many of the sectors that made major contributions in 1990 will reduce their emissions to a significant extent, other sectors that were in 1990 of minor relevance but associated with larger uncertainties will become relatively more important sources (e.g., emissions from aircraft and other sources). This effect will be exacerbated by the general trend to replace sulfur containing fuels such as coal and oil by natural gas.

These effects, which occur throughout the full range of emission sources, lead to an increase in the overall uncertainty for SO_2 emissions in the UK from 11 percent to 15 percent.

A similar picture emerges for NO_x emissions, where the expected value declines by 58 percent (Table 4.13, Table 4.14). Passenger gasoline vehicles, which made the largest contributions in 1990, will move out from the list of the 'top 10' sources, and emissions from diesel trucks will step up to the leading position. Overall uncertainties for the year 2010 are slightly larger than in 1990, mainly due to the uncertainties in projected activity levels.

It is interesting to note, however, that the overall uncertainties in the estimates for national total NO_x emissions is similar, or even slightly smaller, than the uncertainties for SO_2, which might be in contrast to many expert guesses. Indeed, this result is surprising at first glance, since in this calculation the uncertainty of the NO_x emission factors was consistently assumed to be between 50 to 350 percent higher than those for SO_2 – in line with general expert judgment. Uncertainties in the activity rates are obviously identical for SO_2 and NO_x, and the uncertainties of removal rates are similar. As a consequence, as to be expected, uncertainties of the estimates *for individual sectors* are higher for NO_x than for SO_2.

That the estimates of *national total emissions* in the UK are more certain for NO_x than for SO_2 is caused by the fact that SO_2 emissions are dominated (both in 1990 and 2010) by a few source sectors (i.e., power stations burning hard coal, responsible for 67 percent of SO_2 emissions in 1990 and for 39 percent in 2010, and industrial processes). This dominance of a few sectors restricts the potential for compensation of errors for the SO_2 calculations. Since NO_x emissions originate from several sectors with almost equal contributions, compensation of errors is a powerful mechanism leading to lower uncertainties in national total emissions.

It must be stressed that this effect is intrinsically linked to the selected aggregation and only occurs for national total emissions where a substantial potential for error compensation exists. Such a potential might not exist if smaller units are considered, e.g., geographical grid cells or local administrative districts.

It is also clear that this finding depends strongly on the composition of national emission sources, i.e., whether one or two sectors dominate total emissions in a country or not. This is illustrated by the case of Switzerland (Table 4.15 - Table 4.18), where for the year 1990, in the absence of dominating SO_2 emissions from coal power stations, the uncertainty is estimated at 9 percent for SO_2 and at 13 percent for NO_x emissions.

Table 4.11: SO_2 emissions and their uncertainties of the 10 largest emission source sectors in the United Kingdom in the year 1990.

Rank	Fuel	Sector	SO_2 emissions (expected value [kt])	Standard deviation (kt)	95 percent confidence interval
1	Hard coal	Power plants, existing	2550	199	±16 %
2	Heavy fuel oil	Power plans, existing	350	27	±16 %
3		Industrial processes	214	30	±28 %
4	Heavy fuel oil	Refineries	120	9	±16 %
5	Hard coal	Domestic	103	8	±16 %
6	Heavy fuel oil	Industry	89	7	±16 %
7	Hard coal	Industry	82	6	±16 %
8	Diesel	National sea traffic	48	4	±16 %
9	Fuel oil	Domestic	43	3	±16 %
10	Diesel	Road transport	38	3	±16 %
…	…	…	…	…	…
NATIONAL TOTAL EMISSIONS			3812	204	±11 %

Table 4.12: SO_2 emissions and their uncertainties of the 10 largest emission source sector in the United Kingdom for the year 2010.

Rank	Fuel	Sector	SO_2 emissions (expected value [kt])	Standard deviation (kt)	95 percent confidence interval
1	Hard coal	Power plants, existing	379	49	±26 %
2		Industrial processes	216	49	±45 %
3	Heavy fuel oil	Power plants, existing	145	23	±32 %
4	Diesel	National sea traffic	43	6	±26 %
5	Heavy fuel oil	Refineries	29	4	±31 %
6		Air traffic and other uncontrollable sources	27	6	±45 %
7	Heavy fuel oil	Domestic	23	4	±31 %
8	Hard coal	Industry	17	2	±26 %
9	Heavy fuel oil	International sea traffic	17	2	±26 %
10	Hard coal	Domestic	15	2	±26 %
…	…	…	…	…	…
NATIONAL TOTAL EMISSIONS			962	74	±15 %

Table 4.13: NO_x emissions and their uncertainties of the 10 largest emission source sectors in the United Kingdom, 1990.

Rank	Fuel	Sector	NO_x emissions (expected value [kt])	Standard deviation (kt)	95 percent confidence interval
1	Gasoline	Passenger cars	781	100	±26 %
2	Hard coal	Power plants, existing	696	67	±19 %
3	Diesel	Heavy duty trucks	506	65	±26 %
4	Diesel	Off-road machinery	144	18	±26 %
5		Industrial processes	129	23	±36 %
6	Heavy fuel oil	Power plants, existing	69	7	±19 %
7	Diesel	National sea traffic, large vessels	65	8	±26 %
8	Natural gas	Domestic	64	6	±19 %
9	Diesel	National sea traffic, medium vessels	60	8	±26 %
10		Air traffic, other uncontrollable sources	60	11	±36 %
…	…	…	…	…	…
NATIONAL TOTAL EMISSIONS			2839	141	±10 %

Table 4.14: NO_x emissions and their uncertainties of the 10 largest emission source sectors in the United Kingdom for the year 2010.

Rank	Fuel	Sector	NO_x emissions (expected value [kt])	Standard deviation (kt)	95 percent confidence interval
1	Diesel	Heavy duty trucks	208	36	±35 %
2	Hard coal	Power plants, existing	171	25	±29 %
3		Industrial processes	134	34	±50 %
4	Diesel	Off-road transport	88	15	±33 %
5		Air traffic, other uncontrollable sources	86	22	±50 %
6	Natural gas	Domestic	84	12	±28 %
7	Natural gas	Power plants, new	59	9	±29 %
8	Diesel	National sea traffic, large vessels	59	10	±33 %
9	Diesel	National sea traffic, medium vessels	55	9	±33 %
10	Heavy fuel oil	Power plants, existing	49	7	±29 %
…	…	….	…	…	…
NATIONAL TOTAL EMISSIONS			1198	66	±11 %

Table 4.15: SO2 emissions and their uncertainties of the 10 largest emission source sector in Switzerland, 1990.

Rank	Fuel	Sector	SO_2 emissions (expected value [kt])	Standard deviation (kt)	95 percent confidence interval
1	Fuel oil	Domestic	21.6	1.8	±16 %
2		Industrial processes	5.8	0.8	±29 %
3	Diesel	Heavy duty trucks	3.1	0.3	±16 %
4	Hard coal	Industry	2.5	0.2	±16 %
5	Heavy fuel oil	Power stations	1.9	0.2	±19 %
6	Fuel oil	Industry	1.8	0.2	±16 %
7	Diesel	Off-road machinery	1.5	0.1	±16 %
8	Heavy fuel oil	Refineries	1.0	0.1	±16 %
9	Diesel	Light duty vehicles	0.9	0.01	±16 %
10	Hard coal	Power stations	0.7	0.1	±16 %
…	…	…	…	…	…
NATIONAL TOTAL EMISSIONS			43	2.0	±9 %

Table 4.16: SO_2 emissions and their uncertainties of the 10 largest emission source sector in Switzerland for the year 2010.

Rank	Fuel	Sector	SO_2 emissions (expected value [kt])	Standard deviation (kt)	95 percent confidence interval
1	Fuel oil	Domestic	8.6	1.1	±26 %
2		Industrial processes	4.2	1.0	±46 %
3	Hard coal	Industry	3.7	0.5	±26 %
4	Heavy fuel oil	Industry	1.9	0.3	±27 %
5	Heavy fuel oil	Refineries	1.8	0.2	±26 %
6	Light fuel oil	Industry	0.9	0.1	±26 %
7	Wood, waste	Domestic	0.8	0.1	±31 %
8	Waste	Industry	0.8	0.1	±31 %
9	Heavy fuel oil	Power stations	0.8	0.1	±28 %
10	Other	Air traffic, waste treat.	0.5	0.1	±45 %
…	…	…	…	…	…
NATIONAL TOTAL EMISSIONS			26	1.6	±13 %

Table 4.17: NO_x emissions and their uncertainties of the 10 largest emission source sectors in Switzerland, 1990.

Rank	Fuel	Sector	NO_x emissions (expected value [kt])	Standard deviation (kt)	95 percent confidence interval
1	Gasoline	Passenger cars	72.4	9.7	±27 %
2	Diesel	Heavy duty trucks	26.8	3.6	±27 %
3	Diesel	Off-road machinery	15.4	2.0	±26 %
4	Fuel oil	Domestic	13.7	1.3	±19 %
5		Industrial processes	10.0	1.9	±37 %
6	Other	Air traffic, waste, etc.	6.6	1.2	±36 %
7	Diesel	Light duty vehicles	3.0	0.4	±26 %
8	Gasoline	Off-road machinery	2.2	0.4	±39 %
9	Waste	Heat&power generation	2.1	0.3	±32 %
10	Natural gas	Domestic	2.0	0.2	±19 %
…	…	…	…	…	…
NATIONAL TOTAL EMISSIONS			163	10.8	±13 %

Table 4.18: NO_x emissions and their uncertainties of the 10 largest emission source sectors in Switzerland for the year 2010.

Rank	Fuel	Sector	NO_x emissions (expected value [kt])	Standard deviation (kt)	95 percent confidence interval
1	Diesel	Heavy duty trucks	21.0	3.6	±35 %
2	Fuel oil	Domestic	10.9	1.6	±28 %
3	Diesel	Off-road machinery	9.5	1.6	±33 %
4	Gasoline	Passenger cars	6.7	1.8	±55 %
5		Air traffic, other uncontrollable sources	6.6	1.7	±50 %
6		Industrial processes	5.3	1.5	±55 %
7	Waste	Industry	2.9	0.6	±39 %
8	Natural gas	Domestic	2.6	0.4	±28 %
9	Natural gas	Industry	2.2	0.3	±29 %
10	Diesel	Light duty vehicles	2.0	0.4	±34 %
…	…	….	…	…	…
NATIONAL TOTAL EMISSIONS			79	5.2	±13 %

It is interesting to rank the uncertainties with the largest impacts on the final results. As displayed in Table 4.19 for the UK (and Table 4.20 for Switzerland), results are strongly dependent on the specific situation, i.e., the pollutant and the year. For SO_2 in the base year, almost equal uncertainties originate from the activity data and emission factors. If emissions are projected in the future, estimates will be heavily influenced by the uncertainty of projected economic activities. For NO_x, however, base year estimates are more sensitive towards emission factors, while the influence of activity data is lower than for SO_2. NO_x projections depend more on the uncertainties of activity data, and also the removal efficiency is of importance.

Table 4.19: Results from a sensitivity analysis: 95 percent confidence intervals for estimates of national SO_2 and NO_x emissions in the UK. Values describe the 95 percent confidence interval in national total emissions if only the uncertainties of the particular parameter are considered and the uncertainties for all other parameters are excluded.

	SO_2		NO_x	
	1990	2010	1990	2010
Activity data	±8 %	±14 %	±5 %	±8 %
Emission factors	±7 %	±6 %	±9 %	±7 %
Removal efficiency	±0 %	±3 %	±0 %	±3 %
All factors considered	±11 %	±15 %	±10 %	±11 %

Table 4.20: Results from a sensitivity analysis: 95 percent confidence intervals for estimates of national SO_2 and NO_x emissions of Switzerland. Values describe the 95 percent confidence interval in national total emissions if only the uncertainties of the particular parameter are considered and the uncertainties for all other parameters are excluded.

	SO_2		NO_x	
	1990	2010	1990	2010
Activity data	±7 %	±11 %	±6 %	±9 %
Emission factors	±6 %	±5 %	±11 %	±8 %
Removal efficiency	±3 %	±2 %	±4 %	±5 %
All factors considered	±9 %	±13 %	±13 %	±13 %

Uncertainties in National Total Emissions

As a general feature, uncertainties in national total emissions are much smaller than the uncertainties of the estimates for individual sectors. This is a consequence of the assumption that the uncertainties of the individual parameters (except activity rates) are not correlated, so that errors can efficiently compensate each other.

However, there are large differences in the uncertainties of national total emissions of different countries (Table 4.21, Table 4.22). For the year 1990, the 95 percent confidence interval of SO_2 estimates ranges from ±6 percent for France to ±23 percent for the Former Yugoslavia. For NO_x estimates, the range spans from ±8 percent for Greece to ±23 percent for the Former Yugoslavia, and for NH_3 from ±9 percent for Sweden to ±23 percent for Albania. Several factors contribute to larger uncertainties:

- If emissions in a country are dominated by one or two source sectors, there is only a limited potential that errors in the estimates of these sectors can be statistically compensated by other sectors (for instance, this is the case for SO_2 emissions in the UK).
- If parameters (activity data or emission factors) of a large sector are especially uncertain (e.g., lignite burning in the Czech Republic), this will have an influence on national total emissions.
- If many parameters are more uncertain, e.g., in central and eastern European countries.

Uncertainties of SO_2 estimates for the base year are generally between 10 and 15 percent, which is in line with what is expected by many emission inventory experts. More interesting, however, is the fact that, with the specific assumptions about the uncertainties of the input parameters, estimates of NO_x emissions are not significantly more uncertain than SO_2 estimates, which somehow contradicts the general opinion of experts who often suggest (however not based on quantitative methods) for NO_x estimates an "uncertainty" of ±30 percent. Along these lines of arguments we have also assumed in this analysis larger uncertainties in the input data that are relevant for NO_x emissions (e.g., emission factors) and, based on the literature and expert judgment, we believe that the assumed uncertainties are not underestimated. Indeed, the sectoral analysis in the preceding section confirms that sectoral emission estimates for NO_x are clearly more uncertain than those for SO_2 (compare, e.g., Table 4.13 with Table 4.11). Still, the overall uncertainties in national total emissions for NO_x are not significantly higher than those of SO_2. This is mainly caused by the fact that in the case of NO_x several sectors (passenger cars, heavy duty trucks, power stations, process emissions) make similar contributions to total emissions, while for SO_2 the emissions of a few source sectors (power stations) are often dominating and thereby limiting the potential for error compensation. The same mechanism applies to NH_3 emissions, so that also for this pollutant, despite all the large uncertainties in many of the input data, the 95 percent confidence interval for national total emissions ranges between ±10 and ±20 percent.

In most cases, future emissions are more uncertain than estimates for historical years, which is an obvious consequence of the larger uncertainty associated with the projections of activity data. There are, however, notable exceptions mainly in countries in economic transition where, due to the restructuring process, some of the above mentioned factors that led in the year 1990 to large uncertainties become less important, so that the overall uncertainties will decline. This is the case, e.g., for the Czech Republic, where reduced lignite consumption decreases the uncertainties of SO_2 estimates from 20 to 17 percent and that of NO_x estimates from 18 to 16 percent. A similar effect can be observed for the New German Länder.

It should be noted that estimates of emissions from international sea traffic are consistently associated with largest uncertainties, due to the significant uncertainties in many of the relevant input data and the homogeneity of the source sector, which provides only limited scope for compensation of statistically independent errors.

The above findings are to a large extent related to the assumption that errors in input data of the different source sectors are uncorrelated, with the exception of activity data, which are common input to SO_2 and NO_x estimates. Indeed there is little evidence that errors in emission factors and emission control efficiencies (especially for SO_2 and NO_x) would be correlated (e.g., across sectors), and if so, even the sign of a possible correlation could be questionable. For instance, there might be a connection between the sulfur content of coals used in power stations and households. Let's construct a case where the assumed sulfur content of coal used in the domestic sector is too high. There is no generic evidence whether in such a case the sulfur content would be too high in the power sector too (because the statistical information of coal quality in the country is wrong), or whether the high sulfur coal is predominantly used in the power sector, so that the sulfur content of coal for electricity generation should be even higher, if the country average sulfur content is accurate. Similar arguments could be constructed for, e.g., the emission factors of ammonia, where the interdependencies of the various emission stages could lead to negative correlations.

Perfect correlation has been assumed for the activity data that are used to estimate SO_2 and NO_x emissions. Consequently, SO_2 and NO_x estimates are also correlated with each other, depending on the structure of emission sources in a country. In countries with comparably little SO_2 emissions from coal and oil the correlation is weak (e.g., Austria 0.03, Netherlands 0.05), while the correlation could reach a value of up to 0.27 in other cases (e.g., Poland). Most notably, largest correlations (0.29) occur for international sea traffic, which has heavy fuel oil as the only energy source. Correlations will increase in the future, when the importance of potential errors in emission factors will be reduced (due to emission controls), while the uncertainty of the activity data, for which the correlation is specified, will be higher.

Table 4.21: Expected emissions, emission uncertainties and correlation between SO_2 and NO_x emissions in 1990.

	SO_2		NO_x		SO_2/NO_x	NH_3	
	Expected value (kt)	95 percent confidence interval	Expected value (kt)	95 percent confidence interval	Correlation	Expected value (kt)	95 percent confidence interval
Albania	72	±10%	24	±12%	0.08	32	±23%
Atlantic Ocean	641	±19%	911	±26%	0.29		
Austria	93	±9%	192	±10%	0.03	77	±10%
Baltic Sea	72	±19%	80	±26%	0.29		
Belarus	843	±12%	402	±11%	0.16	219	±17%
Belgium	336	±13%	351	±13%	0.04	97	±11%
Bosnia-Herczeg.	487	±19%	80	±15%	0.17	31	±16%
Bulgaria	1842	±21%	355	±13%	0.06	141	±18%
Croatia	180	±10%	82	±14%	0.04	40	±16%
Czech Rep.	1873	±20%	546	±18%	0.11	107	±14%
Denmark	182	±10%	274	±9%	0.28	77	±12%
Estonia	275	±18%	84	±13%	0.12	29	±17%
Finland	226	±8%	276	±9%	0.06	40	±10%
France	1250	±6%	1867	±11%	0.06	810	±11%
Germany, NewL.	4438	±16%	702	±15%	0.18	201	±16%
Germany, Old L.	842	±6%	1960	±11%	0.07	556	±11%
Greece	504	±7%	345	±8%	0.10	80	±21%
Hungary	913	±16%	219	±12%	0.06	120	±18%
Ireland	178	±7%	113	±9%	0.21	127	±13%
Italy	1679	±11%	2037	±9%	0.10	462	±14%
Latvia	121	±8%	117	±11%	0.08	43	±16%
Lithuania	213	±12%	153	±11%	0.11	80	±16%
Luxembourg	14	±14%	22	±12%	0.02	7	±15%
FYRMacedonia	107	±22%	39	±22%	0.09	17	±17%
Mediterranean	12	±19%	13	±26%	0.29		
Rep. of Moldova	197	±10%	87	±10%	0.17	47	±14%
Netherlands	201	±10%	542	±9%	0.05	233	±13%
North Sea	439	±19%	639	±26%	0.29		
Norway	52	±17%	220	±11%	0.02	23	±14%
Poland	3001	±11%	1217	±12%	0.27	505	±17%
Portugal	343	±8%	303	±10%	0.14	77	±10%
Romania	1331	±17%	518	±11%	0.07	292	±15%
Russia Kalinin.	44	±11%	29	±11%	0.13	11	±14%
Russia, Kola-K.	739	±18%	111	±12%	0.06	6	±14%
Russia, Other	3921	±8%	3126	±11%	0.06	1221	±15%
Russia St.Peters.	308	±12%	221	±11%	0.13	44	±14%
Slovakia	548	±12%	219	±12%	0.09	60	±19%
Slovenia	200	±20%	60	±15%	0.09	23	±19%
Spain	2189	±12%	1162	±9%	0.06	352	±15%
Sweden	117	±9%	338	±10%	0.05	61	±9%
Switzerland	43	±9%	163	±13%	0.08	72	±13%
Ukraine	3706	±9%	1888	±10%	0.15	729	±15%
United Kingdom	3812	±11%	2839	±10%	0.23	329	±12%
Yugoslavia	585	±23%	211	±23%	0.09	90	±14%

Table 4.22: Expected emissions, emission uncertainties and correlation between SO_2 and NO_x emissions for the year 2010.

	SO_2		NO_x		SO_2/NO_x	NH_3	
	Expected value (kt)	95 percent confidence interval	Expected value (kt)	95 percent confidence interval	Correlation	Expected value (kt)	95 percent confidence interval
Albania	55	±9%	36	±22%	0.20	35	±23%
Atlantic Ocean	641	±28%	911	±33%	0.62		
Austria	39	±15%	97	±12%	0.07	67	±15%
Baltic Sea	72	±28%	80	±33%	0.62		
Belarus	494	±14%	316	±15%	0.20	163	±17%
Belgium	171	±24%	169	±16%	0.02	96	±17%
Bosnia-Herczeg.	415	±19%	60	±14%	0.23	23	±15%
Bulgaria	846	±22%	297	±17%	0.06	126	±20%
Croatia	70	±15%	91	±19%	0.04	37	±22%
Czech Rep.	336	±17%	312	±16%	0.29	108	±14%
Denmark	146	±20%	141	±10%	0.38	72	±15%
Estonia	107	±24%	49	±16%	0.20	29	±20%
Finland	137	±17%	149	±11%	0.13	31	±13%
France	574	±16%	860	±12%	0.03	780	±14%
Germany, NewL.	141	±15%	219	±12%	0.21	147	±15%
Germany, Old L.	372	±12%	868	±12%	0.12	425	±14%
Greece	508	±13%	342	±10%	0.16	74	±33%
Hungary	227	±28%	159	±15%	0.06	137	±23%
Ireland	119	±15%	79	±10%	0.56	130	±18%
Italy	381	±22%	1013	±13%	0.06	432	±17%
Latvia	71	±10%	84	±14%	0.16	35	±22%
Lithuania	61	±16%	95	±17%	0.11	81	±17%
Luxembourg	8	±36%	10	±17%	0.01	9	±25%
FYRMacedonia	81	±20%	29	±18%	0.17	16	±23%
Mediterranean	12	±28%	13	±33%	0.62		
Rep. of Moldova	117	±11%	66	±13%	0.23	48	±19%
Netherlands	76	±21%	247	±12%	0.03	141	±15%
North Sea	439	±28%	639	±33%	0.62		
Norway	32	±30%	178	±16%	0.06	21	±18%
Poland	1453	±15%	728	±11%	0.35	541	±14%
Portugal	195	±15%	259	±13%	0.18	73	±16%
Romania	594	±20%	458	±13%	0.08	304	±17%
Russia Kaliningr.	18	±16%	25	±18%	0.10	11	±19%
Russia, Kola-K.	473	±34%	86	±14%	0.03	4	±14%
Russia Other	1717	±12%	2517	±15%	0.06	845	±14%
Russia St.Peters.	136	±18%	170	±14%	0.16	33	±14%
Slovakia	137	±13%	132	±16%	0.06	47	±19%
Slovenia	114	±30%	57	±19%	0.11	21	±22%
Spain	1006	±15%	849	±11%	0.10	383	±18%
Sweden	65	±17%	189	±12%	0.10	61	±12%
Switzerland	26	±13%	79	±13%	0.19	66	±20%
Ukraine	1506	±13%	1433	±13%	0.14	649	±14%
United Kingdom	962	±15%	1198	±11%	0.22	297	±17%
Yugoslavia	269	±25%	152	±18%	0.16	82	±14%

4.2 Uncertainties in the Atmospheric Dispersion Calculations

Any calculation of the dispersion of sulfur and nitrogen compounds is loaded with many different types of uncertainties (Table 4.23). Some of the uncertainties are inherent in the atmospheric dispersion model that is used to derive the reduced-form representations of the atmospheric transport of pollutants in RAINS, others are related to the way such reduced-form descriptions are used in the RAINS model.

Table 4.23: Types of uncertainties in the atmospheric dispersion calculations

Model structure	Linearity in atmospheric dispersion of sulfur and nitrogen compounds
	Selected spatial resolution, ignoring in-grid variability
	Country size (country-to-grid)
Parameters	Expected values of parameters for describing chemical and physical processes (conversion rates, deposition rates)
	Inter-annual meteorological variability
Forcing functions	Spatial distribution of emissions within countries
	Accuracy of meteorological data
Initial state	Natural emissions
	Hemispheric background

For practical reasons it was not possible for the authors to address uncertainties of the underlying dispersion model, i.e., the EMEP model on the long-range transport of sulfur and nitrogen compounds in Europe. Recognizing the need for further analysis on this subject, a pragmatic approach was taken instead and the analysis used estimates of the uncertainties introduced by the inter-annual meteorological variability as a surrogate to demonstrate the methodology.

4.2.1 Assumed Uncertainties in Input Data

In the calculations of the RAINS model, fields of sulfur and nitrogen deposition are estimated based on transfer matrices that describe the dispersion of pollutants for the meteorological conditions of an entire year. At the moment matrices are available for 11 years (1985-1995). Since the ecological impacts of acid deposition that are addressed in the RAINS model are caused by long-term accumulated deposition, RAINS calculations use mean transfer matrices that average the dispersion characteristics over these 11 years. Such ‘11 years mean matrices’ are used to analyze the present situation as well as to assess future trends in acid deposition.

Leaving the uncertainties that are inherent in the EMEP model aside, an attempt was made to quantify the uncertainties of the mean transfer matrices that are caused by fact that data for only 11 years are available.

The inter-annual meteorological variability σ_{tc} of the transfer coefficients $tc_{x,i,e}$ can be estimated from the dispersion coefficients of individual years $tc_{x,i,e,t}$:

$$Cov[tc_{x,i,e}, tc_{y,i,e}] = \frac{\sum_t (tc_{x,i,e,t} - tc_{y,i,e})(tc_{y,i,e,t} - tc_{y,i,e})}{n-1} \qquad \text{(Equation 17)}$$

The variance of the transfer coefficients σ_{tc}^2 is the covariance of the transfer coefficient itself for the 11 (n) years.

Unfortunately the available 11 years data do not give us a fully representative picture of the long-term conditions. We use the central limit theorem (e.g., Milton & Arnold, 1995) to extrapolate the standard deviation σ_{tc} of the transfer coefficients computed for the mean of these 11 years data to long-term conditions $\sigma_{\mu\,tc}$:

$$\sigma_{\mu_{tc}} = \frac{\sigma_{tc}}{\sqrt{n}} \qquad \text{(Equation 18)}$$

The central limits theorem also allows us to derive the correlation of the transfer coefficients between the pollutants of a given emitter source, since this correlation is identical with the inter-annual correlation (Schönfeld, 1971):

$$\rho_{tc_{x,i,e}, tc_{y,i,e}} = \frac{Cov[tc_{x,i,e}, tc_{y,i,e}]}{\sigma_{tc_{x,i,e}} \sigma_{tc_{y,i,e}}} \qquad \text{(Equation 19)}$$

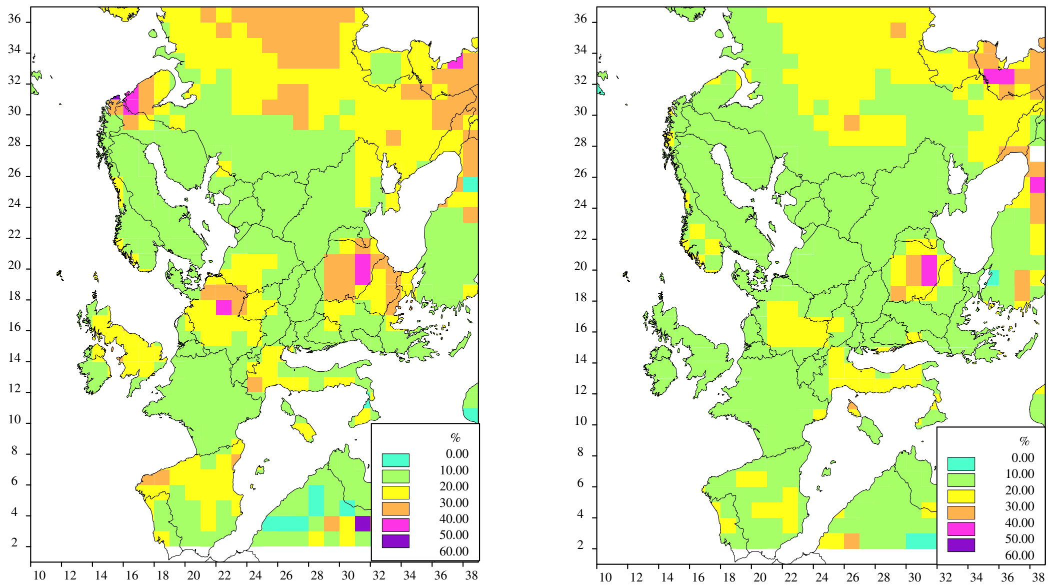
4.2.2 Resulting Uncertainties in Atmospheric Dispersion Calculations

The combined uncertainties in deposition resulting from the uncertainties of the emission and atmospheric dispersion calculations are displayed in Figure 4.1 for 1990 and Figure 4.2 for 2010. These maps show for each grid cell the relative uncertainties (i.e., the confidence intervals divided by the expected values) of the deposition fields of sulfur, oxidized nitrogen, reduced nitrogen (from ammonia emissions) and total (oxidized and reduced) nitrogen.

In the year 1990 estimates of sulfur deposition are most uncertain in the new Länder of Germany, the Kola-Karelia region and in Romania with relative uncertainties in the range between ±40 and ±50 percent. These large uncertainties can be traced back to (i) relatively high uncertainties in the estimates of national emissions, (ii) the uncertainties introduced by the inter-annual meteorological variability, and (iii) situations where deposition at a given site is dominated by a few emission sources (countries), so that there is only a limited potential for compensation of errors. Especially the last cause applies to Kola-Karelia, where sulfur deposition originates largely from the few smelters in the region, and also to Romania, where transboundary contributions do play a smaller role than in other countries.

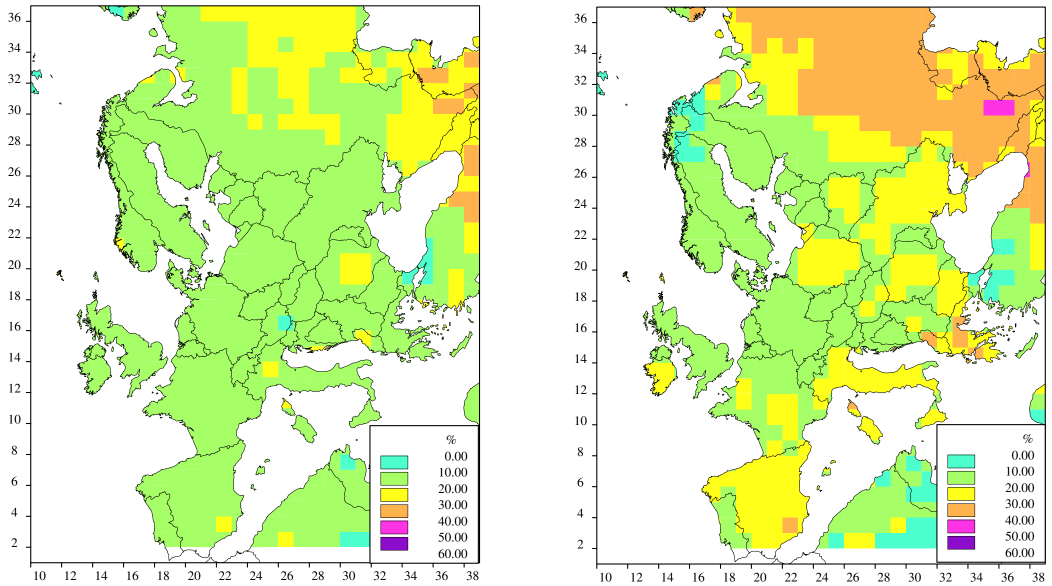
In general, deposition estimates for nitrogen oxides appear more certain than those for sulfur, partly caused by the fact that uncertainties in national NO_x emissions are smaller than those for SO_2. Another reason is that oxidized nitrogen has longer travel distances in the atmosphere, so that the dispersion characteristics are ‘better mixed’ at least for long-term periods and that contributions to deposition from individual countries are more evenly distributed. This increases the potential for error compensation and reduces the uncertainties in estimates of total deposition. Reduced nitrogen, on the other hand, has shorter travel distances with more local dispersion characteristics, which results in comparably larger uncertainties of deposition estimates. Most interesting, however, is the fact that estimates of deposition of total nitrogen, i.e., of oxidized and reduced nitrogen compounds, is more certain than those for the individual compounds, generally within a range of ±10-20 percent. This is a consequence (i) of the larger number of sources, which increases the compensation potential and (ii) the negative correlation in the inter-annual meteorological variability of the transfer coefficients. This negative correlation is explained by the influence of meteorology on the short-term chemical reactions of nitrogen compounds: Sunny and warm weather increases the conversion from NO to NO_3^-, which shortens the travel distance of nitrogen oxides and increases deposition. Ammonia deposition is enhanced by wet weather conditions.

For the year 2010, uncertainties in deposition do not significantly change compared to 1990 in most cases. Exceptions are those countries, which implement less than average emission reductions, so that their domestic contributions to total deposition will increase, which leads to lower potential for error compensation. The uncertainties in ammonia deposition will become a more important factor for total nitrogen deposition.



Sulfur deposition

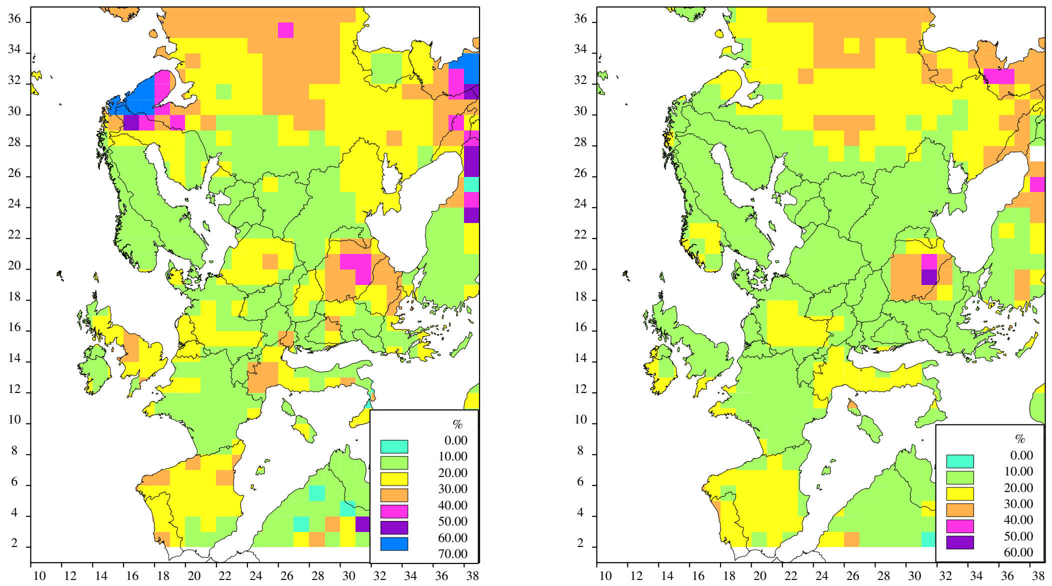
Deposition of oxidized nitrogen



Deposition of total nitrogen

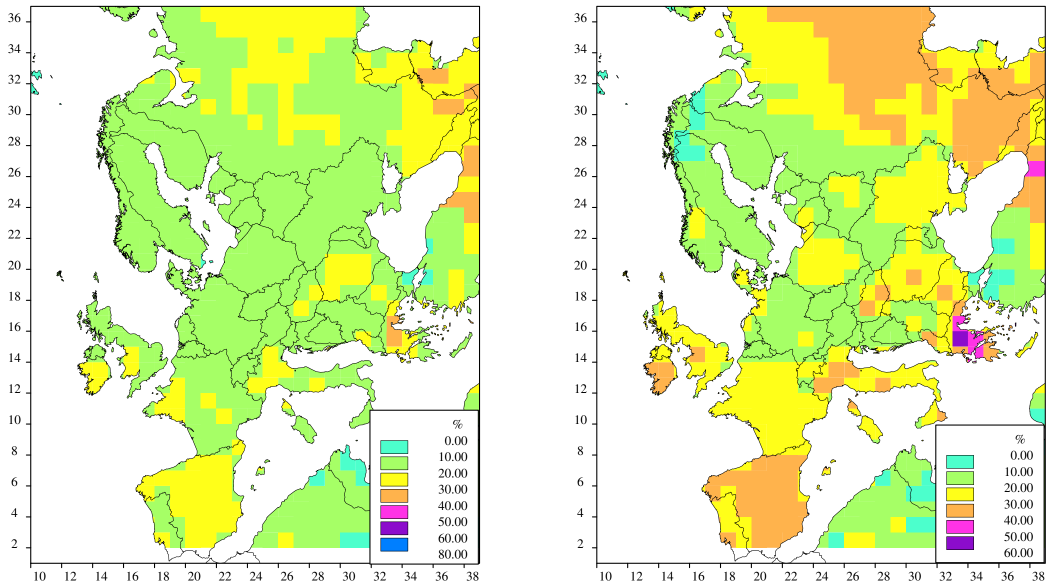
Deposition of reduced nitrogen

Figure 4.1: Ranges of relative uncertainties (confidence interval divided by the expected value) of the deposition estimates for the year 1990.



Sulfur deposition

Deposition of oxidized nitrogen



Deposition of total nitrogen

Deposition of reduced nitrogen

Figure 4.2: Ranges of relative uncertainties (confidence interval divided by the expected value) of the deposition estimates for the year 2010.

4.3 Uncertainties in Ecosystem Protection

Critical loads are derived from model calculations involving a large number of input parameters, all of them associated with significant uncertainties. A methodology was developed to estimate the uncertainty of ecosystem protection isolines from uncertain critical load input data and to compute the uncertainty in ecosystem protection estimates for a given distribution of uncertain depositions. The analysis addressed uncertainties in

- base cation deposition,
- base cation uptake,
- base cation weathering,
- water flux from the bottom of the rooting zone,
- critical aluminum-base cation ratios,
- nitrogen immobilization,
- nitrogen uptake, and
- denitrification.

4.3.1 Uncertainties in Critical Load Data

Within every EMEP grid cell there are many ecosystems, the sensitivity of which is characterized by a critical load. Since both sulfur (S) and nitrogen (N) contribute to acidification, there is no single critical load of acidification. The ecosystem's sensitivity is characterized by the so-called critical load function, a trapezoidally-shaped function in the N-S plane defined by the quantities $CL_{max}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$ (see Hettelingh *et al*., 1995; Posch *et al*., 1995; UBA, 1996). The uncertainties in these quantities have either to be assessed "directly" (e.g., for empirical critical loads) or derived from the uncertainties in the variables used to calculate them, e.g., the variables and parameters needed in the simple mass balance (SMB) model. Since only a few countries provided quantitative information on the uncertainties in their critical load calculations (see Posch *et al.,* 2001), we used the uncertainty ranges for the SMB variables provided by the German and Austrian national focal centers. These ranges are summarized in Table 4.24.

Since the equations for calculating $CL_{max}(S)$ and $CL_{max}(N)$ with the SMB model are non-linear, no analytical expressions can in general be derived for their moments (mean and variance) from the moments of the input parameters. Thus Monte Carlo simulation was used to obtain the variation in these critical load quantities. We assumed that the uncertainties in the SMB parameters were uniformly distributed around their median values with the ranges given in the Table 4.24. Furthermore, we assumed that the parameters were uncorrelated, with the exception of base cation and nitrogen uptake, for which full correlation was assumed. Performing 2000 Monte Carlo runs, the coefficient of variation (CV) for $CL_{max}(S)$ was 22 percent for Germany and 25.4 percent for Austria. The CVs for $CL_{min}(N)$ were 7.5 percent and 8.8 percent and those for $CL_{max}(N)$ 12.5 percent and 17.5 percent, respectively. It is interesting to note that despite the fairly large differences in the parameter uncertainties between the two countries, the variation in the critical load values does not differ that much.

Table 4.24: Uncertainty ranges for SMB variables provided by Germany and Austria.

Variable	Germany	Austria
Base cation deposition	±20 %	±30 %
Base cation weathering	±20 %	±40 %
Base cation uptake	±15 %[a]	±20 %
Precipitation surplus	±15 %	±50 %
Nitrogen uptake	±15 %[a]	±20 %
Nitrogen immobilization	±5 %	-[b]
Denitrification fraction (f_{de})	±20 %[c]	-[b]
Gibbsite equilibrium constant	±20 %[d]	±20 %[d]
Critical Al:Bc ratio	±10 %	-[b]

Notes:

[a] Derived from 10% variation in BC/N content and biomass.

[b] No value given; German values have been used.

[c] Value originally provided was 10%.

[d] Assigned by the Coordination Center for Effects (CCE).

4.3.2 Resulting Uncertainties in Ecosystem Protection Isolines

For every pair of sulfur and nitrogen deposition (N_{dep}, S_{dep}), the percentage (area) of ecosystems that is protected (or exceeded) can be determined by checking whether the deposition is below or above the critical load function. Connecting the points of equal protection yields the so-called *protection isoline,* a unique function of the angle Φ=arctan(S_{dep}/N_{dep}) in the N-S plane. These protection isolines (or rather polygonal approximations thereof), computed for a sufficiently large number of percentage values for every EMEP grid square covering Europe, are then used in integrated assessment models. Detailed definitions and procedures for computing protection isolines can be found in Posch *et al*. (1997).

In an earlier exercise (Suutari *et al*., 2001a,b) the uncertainty in the protection isolines was assumed identical to the uncertainty in the critical load function. This is a rather crude approximation, since it assumes full correlation between the individual critical loads in a grid cell. It results in higher uncertainty estimates for the isolines and thus represents a ‘worst case’. Under the more realistic assumption of an independent variation (uncertainty) in the critical load functions, uncertainties can cancel out and the variation can be reduced considerably. We demonstrate this phenomenon with a one-dimensional example:

In Figure 4.3(a) an example of a cumulative distribution (CDF) of critical loads (critical load numbers, not functions!) is shown. Also shown are their individual uncertainty ranges (one standard deviation). We obtain the uncertainty range of the CDF by randomly drawing a value from each CL-range, sorting them and thus create a new CDF. This is repeated many (several thousand) times. From the many random CDFs the mean and range (standard deviation) is calculated for every value (smallest, second smallest, …, largest) and these define the uncertainty range of the CDF. Figure 4.3(b) was created from the data in Figure 4.3(b) assuming that the values are independently and uniformly distributed around their respective mean (±25 percent). Such an aggregation process reduces for most parts of the CDF the uncertainties considerably, a phenomenon also observed in Barkman (1998).

One has to bear in mind, that the data in Figure 4.3(b) do *not* represent individual critical loads, but the means and uncertainty ranges of the different percentiles of the CDF in Figure 4.3(a). While any in-grid spatial information is lost, this does not matter for our application, since we compare the CDF to a single (average) deposition value for the grid. In the example shown in Figure 4.3 (a) we assumed statistical independence between the different critical loads. With an increasing correlation, the uncertainty bands would become wider, and complete correlation would leave the uncertainty ranges unchanged (i.e., Figure 4.3(b) be identical to Figure 4.3(a)). The reduction of the uncertainty ranges also depends on the degree of overlap between the individual uncertainty ranges. If there were no overlap, there would be no narrowing of the uncertainty band, since the order of the randomly varied critical loads would never change (like for some points near the top of the CDF in Figure 4.3).

This same reduction in the uncertainty ranges can occur, of course, also when dealing with critical load *functions*. Protection isolines are nothing else than two-dimensional percentiles of the 'CDF' of critical load functions.

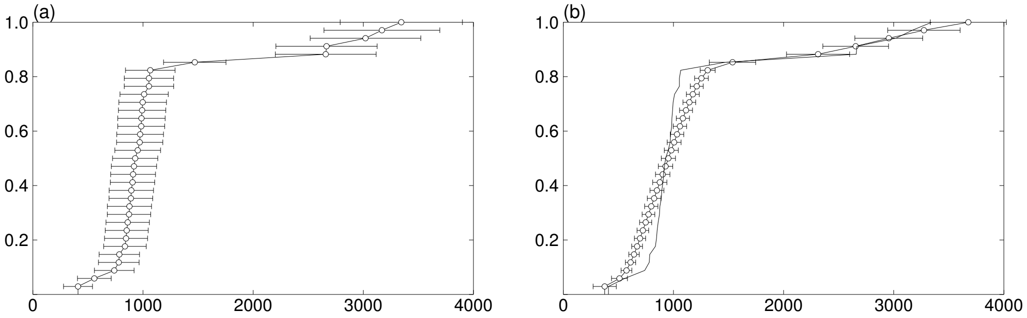


Figure 4.3: (a) Examples of critical load (CL) values (white circles) displayed as cumulative distribution function (CDF). The horizontal interval at every CL value indicates its uncertainty range. The thin line connecting the CL values is a guide for the eye only (and the usual way to plot a CDF). (b) CDF of the mean values of the smallest, 2nd smallest, …, largest values of every realization of randomly and independently selected values from (a) together with their (in generally smaller) uncertainty ranges. Also shown is the CDF of (a) as thin line.

The uncertainty ranges of the protection isolines are derived from the uncertainties in the critical load functions, each of which defined by the three quantities $CL_{max}(S)$, $CL_{min}(N)$ and $CL_{max}(N)$. It is virtually impossible to derive explicit formulae for the uncertainty of protection isolines from the uncertainty of the critical loads, because the calculations are nonlinear, including division and sorting. Therefore, Monte Carlo simulation has been used again to estimate the uncertainty parameters of the protection isolines.

Due to the lack of more detailed data, a CV of 25 percent for $CL_{max}(S)$ and of 10 percent for $CL_{min}(N)$ has been used to describe the uncertainty in the critical load functions all over Europe. These values are on the 'precautionary side' of the CVs derived from the German and Austrian data. From the Monte Carlo simulations carried out in the previous section, it appears that $CL_{max}(S)$ is well described by a Gaussian distribution and $CL_{min}(N)$ by a uniform distribution. While $CL_{max}(S)$ and $CL_{min}(N)$ are uncorrelated (they don't have a single parameter in common), $CL_{max}(N)$ depends strongly on those two parameters; it is given by:

$$CL_{max}(N) = CL_{max}(S)+CL_{min}(N)/(1-f_{de}) \qquad \text{(Equation 20)}$$

The randomized $CL_{max}(N)$ was thus obtained from the random $CL_{max}(S)$ and $CL_{min}(N)$ and a random f_{de}, drawn from a uniform distribution varying 20 percent around the deterministic (given) value. In this way randomized critical load functions were obtained. From these, using the procedures described in Posch *et al.* (1997), the nodes (x_k,y_k), k=0,…, K, of a polygon describing, say, the *n-percent* protection isoline, was obtained for each realization. From the all these realizations the mean and standard deviation of a one-dimensional distribution along the ray through the origin with angle $\Phi_k=arctan(y_k/x_k)$ was calculated (see Figure 3.3). For an arbitrary angle Φ we determine the sector k, i.e., the angles Φ_{k-1} and Φ_k with $\Phi_{k-1}\leq\Phi<\Phi_k$, and interpolate (linearly in Φ) mean and standard deviation. Integrating along a ray with respect to the distance from the origin and subtracting from 1 yields for a deposition pair (N_{dep},S_{dep}) lying on that ray the probability to protect *n* percent of the ecosystems within the grid square (see Figure 3.4). Viewed as a function in Φ, these cumulative distribution functions form a protection probability surface in the N-S plane for the *n percent* protection isoline (see Figure 3.5). This surface defines the probability P_n to protect *n* percent of the ecosystems for any given nitrogen and sulfur deposition (Equation 15).

The above procedure was carried out for the most recent critical loads data base described in Posch *et al.* (2001). This data base consists of about 1.5 million critical load functions in about 500 EMEP (150×150 km^2) grid cells in Europe. In the Monte Carlo simulations described above, 300 random variations of each critical load function in every grid cell were used to compute the mean and standard deviation in every grid cell for a set of 9 protection isolines (100, 98, 95, 90, 75, 50, 25, 10 and 0 percent protection) approximated by 19 nodes. These computations take about three hours on a 450 MHz PC.

4.3.3 Resulting Uncertainties in Ecosystem Protection

The main purpose to derive isolines of ecosystem protection is to estimate the percentage of ecosystems protected from acidification in a grid square for given depositions. If the N and S depositions are known precisely, i.e., if they do not have any uncertainties associated with them, P_n (Equation 16) can be directly used to calculate the probability to protect *n* percent of the ecosystem area within the grid cell. However, there are also uncertainties in the deposition estimates as described in the previous sections. Therefore, the protection probability is obtained by summing the protection probabilities weighted by the probability of deposition, and this is effected by the integral of Equation 16.

Finally, to get the overall uncertainty in ecosystem protection in a grid cell for a given deposition scenario one has to evaluate Equation 16 for a sufficient number of protection percentages *n* ($0 \leq n \leq 100$). In this way, one obtains the cumulative distribution function (CDF) of ecosystem protection (see Figure 4.4). For the given deposition scenario this CDF allows to read any confidence level for ecosystem protection, i.e., the probability to protect at least *n* percent of the ecosystem area in the grid cell.

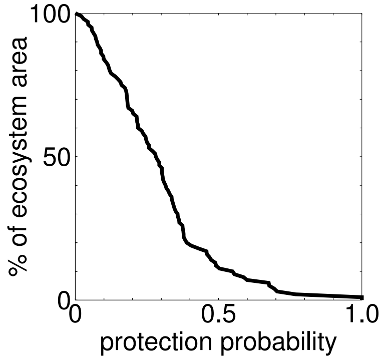


Figure 4.4: Example of a (inverse) cumulative distribution of ecosystem protection probability for a given N and S deposition distribution.

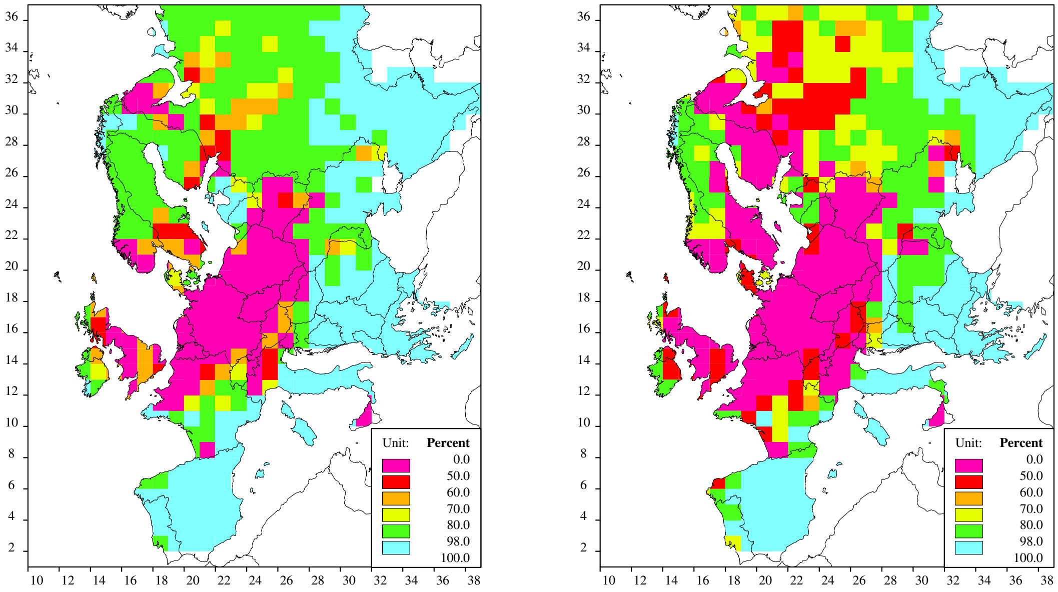
To compute the uncertainty in the ecosystem protection for the whole of Europe we also need the uncertainty in N and S deposition. Since the protection uncertainty is highly dependent both on the magnitude of the expected deposition and the deposition uncertainty, we analyze the protection uncertainty for two RAINS emission scenarios: The sulfur and nitrogen emissions for the years 1990 and 2010, assuming for the latter that the emission reductions of the Gothenburg Protocol are fully implemented. Uncertainties of deposition estimates are discussed in the preceding section.

Uncertainties in ecosystem protection in Europe are computed from the uncertainties of the deposition and the uncertainties of protection isolines for every protection isoline in every grid cell covering Europe. The results of this computationally demanding exercise are displayed in Figure 4.5 for 1990 and Figure 4.6 for the emissions of the Gothenburg Protocol in the year 2010. While Figure 4.5(a) and Figure 4.6(a) display the results from a deterministic calculations, Figure 4.5(c) and Figure 4.6(c) present the range of uncertainty, expressed as the difference in the percent of ecosystems protected with five percent confidence level (Figure 4.5(b) and Figure 4.6(b)) and 95 percent confidence level (Figure 4.5(d) and Figure 4.6(d)).

Uncertainties in ecosystems protection are determined by the uncertainties of the deposition estimates and the uncertainties of protection isolines. While we found that error compensation is one of the most important mechanisms determining uncertainties of emission and deposition estimates, for ecosystems protection the binary nature of the protection criterion (i.e., protected or not protected) becomes a dominating factor at places where deposition is close to critical loads or where critical load values for ecosystems in a grid cell are very similar. Thus, the uncertainty range is highest in grid squares where deposition is close to critical loads and/or where ecosystems do not differ greatly in terms of their critical loads. This can be seen for 1990 in France and Russia, where the uncertainty ranges are largest because deposition is close to critical loads, and critical load values are few and/or have steep gradients.

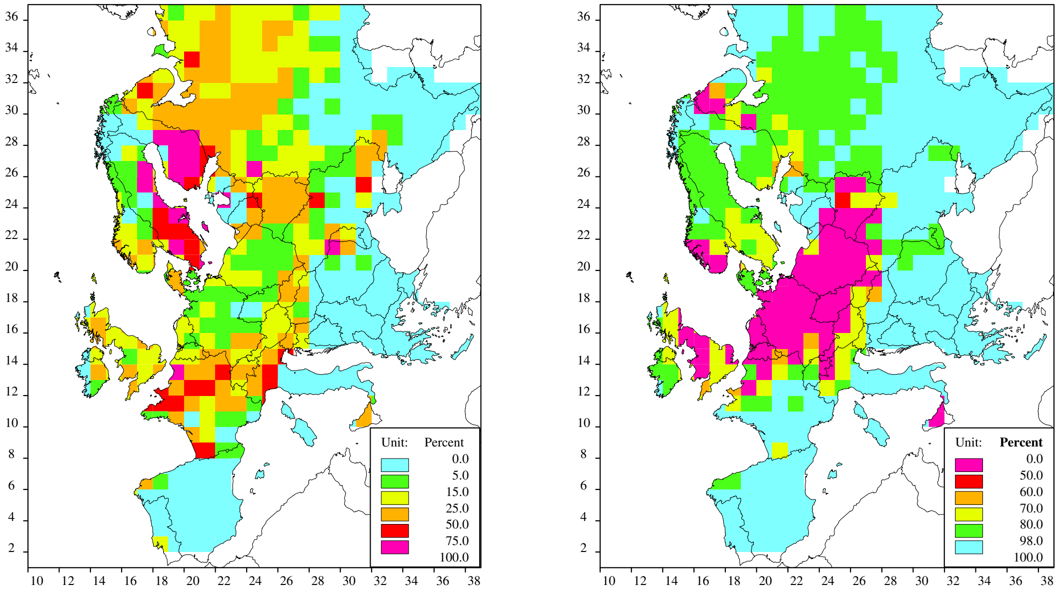
In 2010, the expected value of ecosystems protection shows large improvement. However, uncertainty ranges are still significant and extend in many areas from 25 to 100 percent of the ecosystems.

The Gothenburg Protocol and the analyses for the EU Emission Ceilings Directive focused on the median estimate, for which there is a 50 percent probability that the environmental targets will be achieved and a 50 percent probability that the targets will be missed.



Deterministic case, i.e., ecosystems protected with 50 percent probability

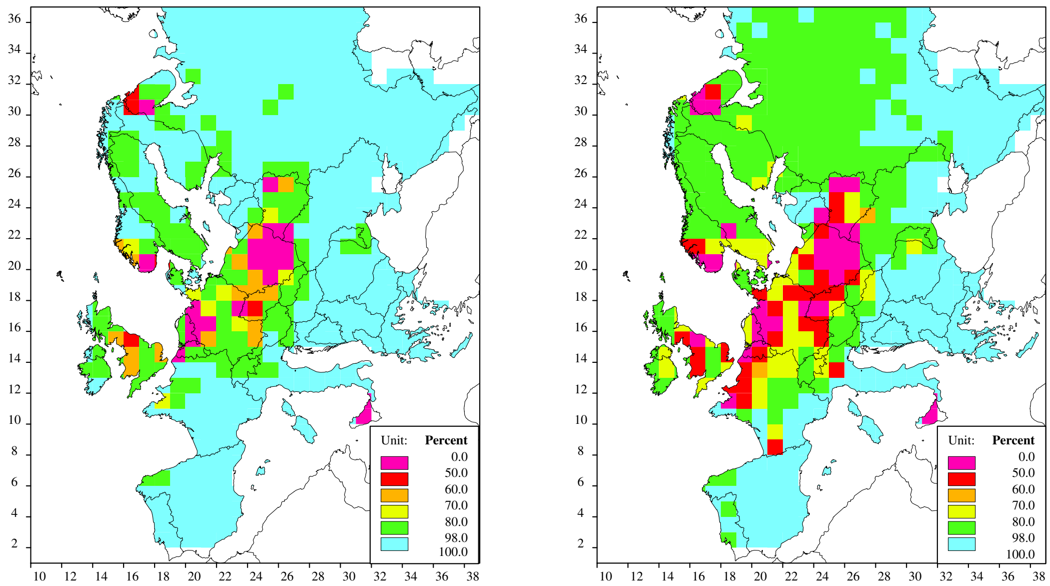
Ecosystems protected with 95 percent probability



Uncertainty range (in percent of ecosystems area)

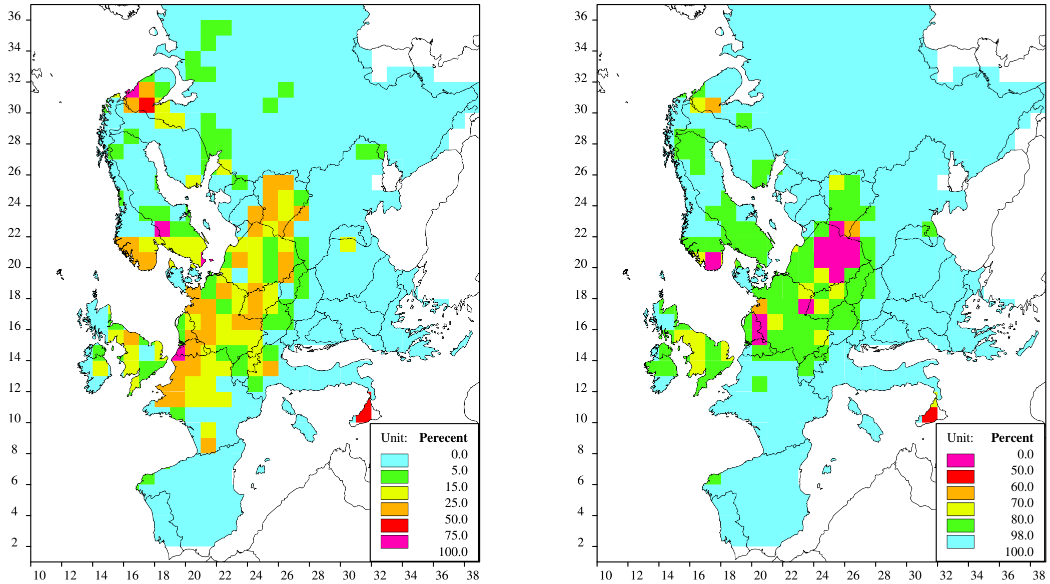
Ecosystems protected with 5 percent probability

Figure 4.5: Estimates of the percentage of protected ecosystems in the year 1990.



Deterministic case, i.e., ecosystems protected with 50 percent probability

Ecosystems protected with 95 percent probability



Uncertainty range (in percent of ecosystems area)

Ecosystems protected with 5 percent probability

Figure 4.6: Estimates of the percentage of protected ecosystems in the year 2010.

Table 4.25 shows for the year 2010 the percentage of ecosystems area that remains unprotected with certain probability. While with 50 percent probability 4.6 percent of Europe's ecosystems will remain unprotected (and 5.9 percent in the EU-15), there is a five percent probability ('the worst case') that in 2010 in Europe more than 9.6 percent (and 13.8 percent in the EU) remain unprotected. On the other hand, there is also a five percent chance (the 'best case') that only less than 0.9 percent (and 2.8 percent in the EU-15) remain unprotected leaving only few areas in Europe (at the Dutch/German border and in southern Norway) with excess deposition at more than 50 percent of the ecosystems area.

Thus, in the worst case (with five percent probability), Europe will massively fail to reach the envisaged environmental targets of the Gothenburg Protocol.

Table 4.25: Expected percentage of ecosystem area per country that remains unprotected in the year 2010 with different levels of confidence. The median (50%) estimate was used for negotiations of the Gothenburg Protocol.

	Probability						
	5%	10%	25%	50%	75%	90%	95%
Austria	3.7%	4.4%	5.8%	7.5%	9.9%	11.7%	12.6%
Belgium	14.6%	16.2%	19.0%	27.8%	32.1%	40.3%	46.2%
Denmark	1.1%	1.6%	2.3%	3.8%	5.4%	6.4%	6.6%
Finland	1.3%	1.5%	2.2%	3.4%	5.0%	6.1%	7.2%
France	0.2%	0.3%	0.6%	2.1%	5.9%	11.3%	16.1%
Germany	14.0%	15.5%	19.1%	24.8%	31.1%	37.1%	38.8%
Greece	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ireland	1.4%	1.8%	2.5%	3.6%	5.1%	7.1%	7.7%
Italy	0.6%	0.8%	1.2%	2.2%	3.2%	5.4%	6.5%
Luxembourg	3.0%	5.0%	6.0%	8.0%	10.0%	20.0%	24.0%
Netherlands	43.3%	45.1%	49.8%	58.4%	64.6%	68.4%	69.6%
Portugal	0.0%	0.0%	0.0%	0.2%	0.7%	0.9%	1.5%
Spain	0.1%	0.1%	0.2%	0.3%	0.5%	0.5%	0.7%
Sweden	2.4%	2.8%	3.8%	5.3%	7.2%	13.0%	13.9%
UK	9.7%	10.6%	12.3%	15.5%	18.5%	20.9%	21.6%
EU-15	2.8%	3.2%	4.1%	5.9%	8.3%	12.1%	13.8%
Albania	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Belarus	10.1%	12.1%	16.0%	21.8%	27.4%	31.7%	35.2%
Bosnia-H	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.5%
Bulgaria	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Croatia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Czech Rep.	21.7%	23.6%	28.2%	35.1%	42.1%	48.2%	50.2%
Estonia	0.3%	0.3%	0.6%	1.5%	2.7%	4.5%	5.8%
Hungary	5.3%	5.8%	6.8%	8.8%	10.2%	12.1%	12.6%
Latvia	0.0%	0.0%	0.0%	0.1%	0.6%	1.1%	1.8%
Lithuania	0.3%	0.4%	0.5%	2.8%	4.7%	9.2%	21.3%
Norway	6.8%	7.3%	8.6%	10.9%	13.8%	17.4%	19.2%
Poland	33.6%	34.8%	38.5%	43.9%	49.8%	53.1%	54.6%
R.Moldova	0.6%	0.8%	1.1%	2.6%	3.3%	4.3%	4.7%
Romania	0.0%	0.1%	0.2%	0.7%	1.1%	1.7%	2.2%
Russia	0.4%	0.5%	0.8%	1.3%	2.3%	3.6%	4.5%
Slovakia	7.9%	8.9%	10.6%	14.4%	18.0%	20.6%	21.5%
Slovenia	0.3%	0.3%	1.1%	1.9%	2.8%	3.8%	4.6%
Switzerland	1.3%	2.2%	3.2%	5.4%	7.9%	11.2%	12.9%
FYRMacedonia	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Ukraine	4.4%	5.3%	7.2%	9.7%	12.0%	13.4%	15.6%
F.Yugoslavia	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%
Non-EU	2.4%	2.6%	3.2%	4.1%	5.5%	7.0%	8.1%
TOTAL	2.5%	2.8%	3.4%	4.6%	6.3%	8.3%	9.6%

4.3.4 Accounting for In-grid Variation of Acid Deposition

The continental scale analysis uses for each grid cell (150*150 km) the calculated average deposition and compares this single value with the critical load (distribution) for the various ecosystems. In reality, however, it is known that deposition shows significant in-grid variation, e.g., due to small scale variations in the amount of precipitation or through more efficient 'filtering' of pollutants at rough surfaces such as forest ecosystems. In this procedure, two sources of uncertainty can be identified:

- The currently used deposition estimates represent averages over all land cover types. However, dry deposition is greatly effected by the land cover (surface roughness), and therefore the ecosystems we consider (e.g., forests) may receive significantly different (larger) amounts of deposition than the grid square average, leading to a bias in ecosystem protection estimates.
- An error is introduced by the differences in spatial resolution between deposition and critical load data. Within an EMEP grid cell there is (most likely) a (large) variation in the local deposition. Since we do not know the detailed deposition pattern within grid cells, we have to take into account the in-grid variability of the deposition as an additional source of uncertainty. In addition, there is likely to be some correlation between sulfur and total nitrogen deposition in every grid cell.

To show the impact of these two sources of uncertainty on the estimated protection percentages, we use German forest critical loads for acidity as an example. An earlier study conducted by the University of Stuttgart together with RIVM (Gauger *et al.*, 2000) determined small scale variations in acid deposition over Germany. Using the EUTREND model and detailed land use data, small-scale variations in sulfur and nitrogen deposition were determined with a 500×500 meter resolution. From this study, the distributions of sulfur and nitrogen deposition over the forested area in every EMEP150×150 km^2 grid cell covering Germany were obtained. The following parameters were distinguished: The differences (bias) between local deposition and the grid average deposition of sulfur and nitrogen as calculated by Gauger *et al.* (2000), (ii) the variation in deposition over all forest locations in the grid cell; (iii) and the correlation between sulfur and nitrogen deposition. These parameters allow for characterization of the bivariate sulfur and nitrogen deposition distribution in each grid cell.

These variations in sulfur and nitrogen deposition and their correlation were used for Monte Carlo simulations for computing the uncertain ecosystem protection isolines in the following way: When sampling a randomized critical load function according to the procedure defined above, the origin of the function was randomly shifted in addition, according to the in-grid deposition variation. This was done by drawing pairs of uniformly distributed random numbers with zero mean and variance equal to the N and S deposition variance of the respective grid cell. The desired correlation between these numbers was ensured by applying a procedure described in Iman and Conover (1982). Thus, the protection isolines distributions obtained in this way contain already the in-grid variation and correlation of S and N deposition. The bias, i.e., difference between the grid average distribution and grid-average distribution to forests, was taken into account when computing ecosystem protection for a given deposition scenario.

The influence of the different uncertainties in the deposition on the ecosystem protection was studied by computing the (inverse) cumulative distributions (CDFs) of protection probabilities for (forest) ecosystems (cf. Figure 4.4) in every grid square of Germany for sulfur and nitrogen deposition in 1990 (Figure 4.7) and in 2010 after the full implementation of the Gothenburg Protocol (Figure 4.8). In both Figures the upper left maps show the protection probability CDFs without taking into account the uncertainty due to in-grid variability and bias in the nitrogen and sulfur deposition ("reference case"). The upper right maps show these CDFs when only in-grid variation is considered. The lower left maps shows the CDFs when taking into account the bias in the deposition; and the lower right maps show the influence of both bias and in-grid variation of the deposition estimates on ecosystem protection.

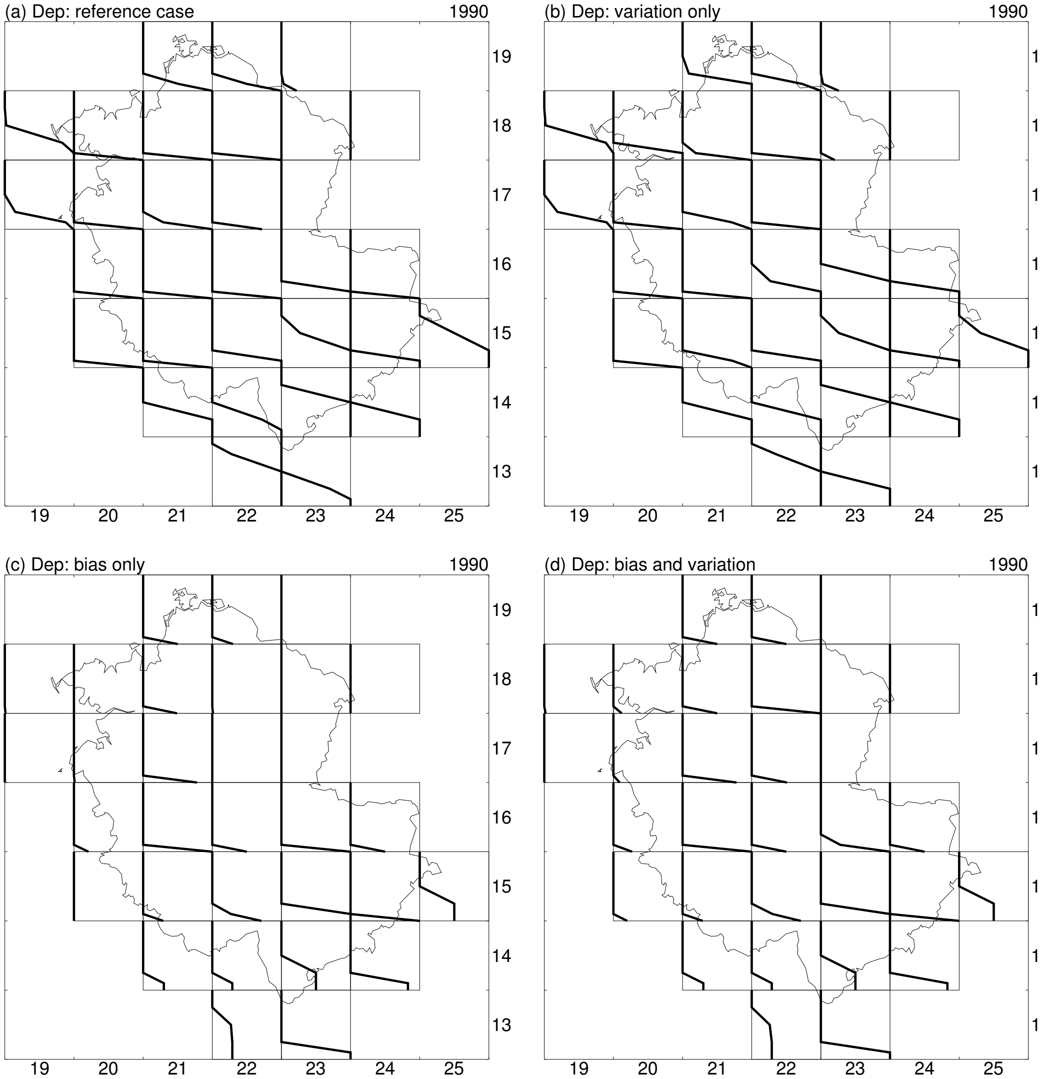


Figure 4.7: Inverse cumulative distribution functions (CDFs) of (forest) ecosystem protection probabilities in the EMEP150 grid cells covering Germany for 1990. (a) Without taking into account the uncertainty due to in-grid variability and bias in sulfur and nitrogen deposition ("reference case"); (b) adding only in-grid variation; (c) adding only the bias in the deposition; and (d) adding both bias and in-grid variation for the deposition estimates in the 150×150 km^2 grid system.

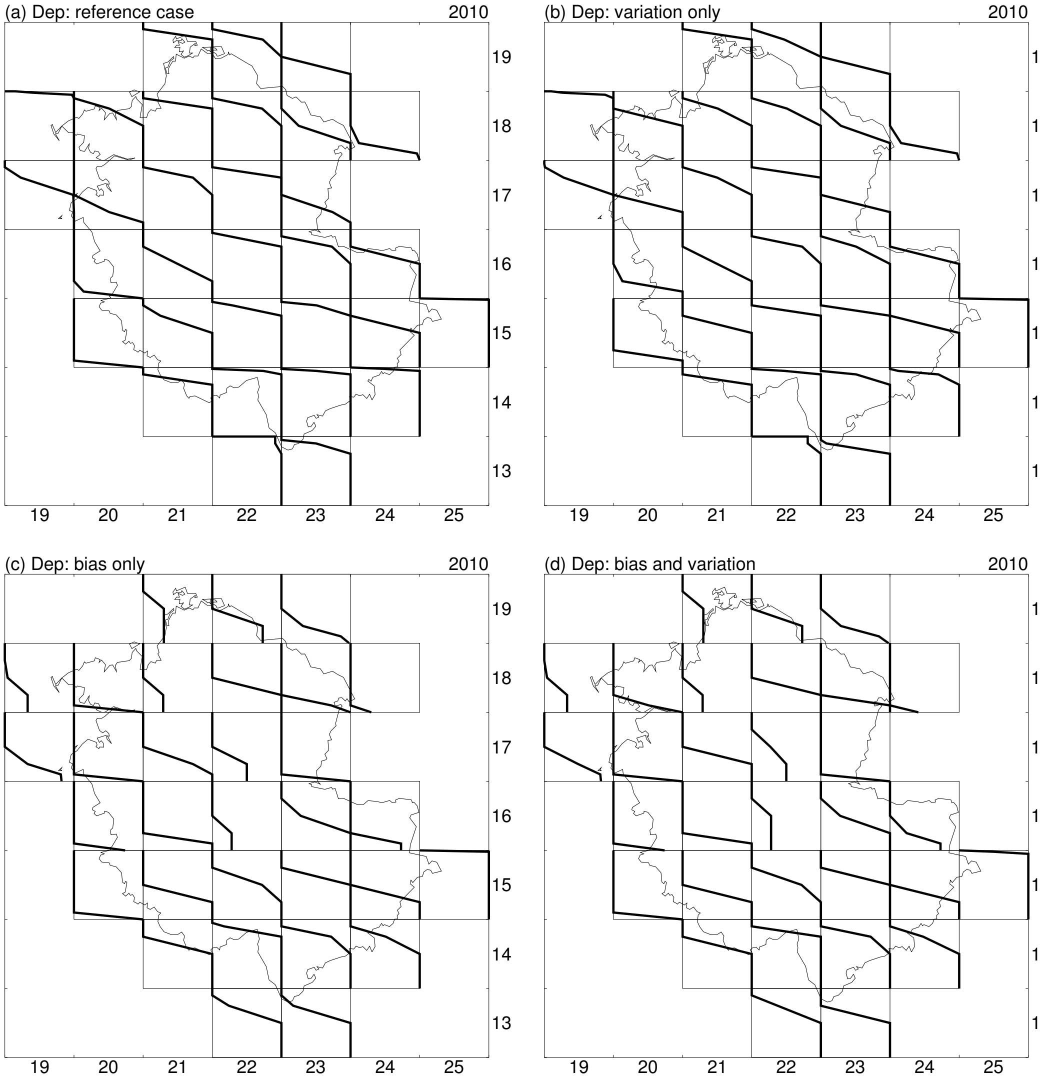


Figure 4.8: As Figure 4.7, but for the 2010 N and S deposition after full implementation of the Gothenburg Protocol.

As expected, and as can be seen from Figure 4.7 and Figure 4.8, the influence of the bias in the deposition estimate on the resulting protection percentages is much larger than the in-grid variation. This is obvious, since the bias shifts the expected ("deterministic") values, whereas the (symmetric) in-grid variability only adds to the overall uncertainty, but does not change the expected value. According to these preliminary results, hardly any forest ecosystems can be protected with reasonably probability in most of Germany. The situation improves considerably in 2010, but when demanding a high probability of protection, the fraction of the forest area for which this can be achieved remains small in many grid cells.

5 Discussion and Conclusions

This paper makes a first attempt to propagate uncertainties through the RAINS model calculations from economic activity to the protection of ecosystems. While the methodology is now developed and an example implementation is available, one should be careful when drawing quantitative conclusions from this analysis. Within the given time it was not possible to include the full range of parameters that contribute to uncertainties in the analysis, so that the results presented in this paper are based on an incomplete representation of existing uncertainties. Furthermore, for many of the factors that are included in the analysis it was only possible to derive preliminary quantifications of their uncertainties, and more work is required to obtain improved estimates.

Given these limitations the discussion and conclusions in this paper are restricted to general features of uncertainties. Numerical results could change in future if additional factors are considered.

5.1 General Observations about Uncertainties

As a general observation we found it much more difficult to quantify uncertainties on a solid basis than, e.g., mean values that are used in traditional deterministic analyses. Therefore, we consider the quantification of the **uncertainties** themselves as the **most uncertain** element in the **uncertainty analysis**. Indeed, many assumptions on the CV of input data to the different modules could be justified only in a very tentative manner and further work will be necessary to improve the understanding for quantifying uncertainties of input data.

This observation holds despite the methodological approach, which relies solely on the first and second moments of model parameters (i.e., the means, the variances and correlations) and, in contrast to many other approaches to uncertainty analysis, does not require assumptions about distributions, which are even more difficult to establish on a firm basis.

Furthermore, we found it most difficult to quantify (in several cases even the sign of) correlations between input parameters. As a consequence we could only consider a very limited number of correlations, accepting that this limitation could have bearings on the conclusions of the analysis. The extent to which the variability of RAINS-outputs regarding protected ecosystems is affected by the 'uncertainty of uncertainties' or the 'uncertainty of expert opinion' will be subject of future work.

The error propagation methodology developed for this paper is only applicable to additive and multiplicative models. It cannot be used for non-linear models, e.g., for determining uncertainties of critical loads from input parameters, or more generally, for any process involving ranking/substituting of options.

It is pointed out in this paper at several places that quantitative uncertainty estimates can only be computed for specific model outputs. General notions like 'the uncertainty of a given model' do not appear particularly useful concepts. Different types of model output have different uncertainties, as demonstrated, e.g., in the case of sectoral and national total emissions. This also reinforces the basic concept that each model has its specific purpose for which it was constructed and for which the control of uncertainties is a critical issue. Using the same model for other endpoints might put the uncertainties in a completely different context and requires careful analysis of these implications.

5.2 Uncertainty of Emission Estimates

It was found that the uncertainties in calculations of emissions, which add up a large number of multiplicative operations for individual sources, are strongly determined by the potential for error compensation. This potential is larger - and therefore the uncertainties are smaller – if more elements of similar sizes are included and if there is no (emission) source that makes a dominating contribution.

Therefore, in general RAINS model estimates of sectoral emissions are more uncertain than national total emissions. The error compensation leads to the situation that in many countries levels of national SO_2 emissions turn out to be more uncertain than those of NO_x and even NH_3, despite uncertainties in many of the input parameters for NO_x and NH_3 calculations being larger than those for SO_2.

This finding has an implication on the optimal design of emission inventories, suggesting that more resolved emission inventories should be associated with less overall uncertainties. However, the potential for such improvements is limited by the associated need for additional information at the more resolved level with equal quality. Simple disaggregation of sectors without additional genuine information would just introduce strongly correlated terms in the analysis, which in turn will not influence the uncertainties of the overall estimate.

Real improvements in emission inventories are inextricably linked to the availability of additional information and deeper insight into the correlations of parameters.

5.3 Uncertainties of Deposition Estimates

For practical reasons the analysis conducted for this paper could not explore the full range of potential factors that contribute to the uncertainties in the estimates of atmospheric dispersion of pollutants. Further insights could be gained through additional analysis, e.g., with the EMEP dispersion model.

The analysis, which focused on the inter-annual meteorological variability, shows that also for deposition estimates error compensation is an important mechanism with direct impacts on the uncertainties of results. Deposition estimates are more uncertain if deposition at a given site is dominated by the emissions of single source (region), e.g., at the Kola Penninsula and in Romania. Also an uneven distribution of emissions within a country (e.g., if there is only one large power station making a dominant contribution to national emissions) leads within the country to larger uncertainties in the deposition field due to the inter-annual meteorological variability.

In general, the combined uncertainties of emission estimates and of the inter-annual meteorological variability leads to similar uncertainties of sulfur and reduced nitrogen (NH_3) deposition fields, while for oxidized nitrogen uncertainties turn out to be slightly lower.

The analysis reveals an interesting aspect showing lower uncertainty in the field of total nitrogen deposition than for the two individual components. This is caused by a negative correlation between NO_x and NH_3 deposition, which was identified from the EMEP model calculations for areas close to emission sources as a consequence of meteorology and short-term chemical reactions. Sunny and warm weather increases the conversion rate from NO to NO_3^-, which shortens the travel distance of nitrogen oxides and increases local deposition. For ammonia, larger rates of local (wet) deposition occur in wet weather conditions.

5.4 Uncertainties of Estimates on Ecosystems Protection

As shown by this paper, a method to analyze the uncertainties in the protection of ecosystems due to the exceedance of critical loads on a European scale is available. To get the most out of such an analysis, good quality data characterizing the uncertainties is needed, i.e., the analysis should not be questioned due to the “uncertainties in the uncertainties”. An uncertainty analysis as described in this paper does not only provide information on the confidence levels which can be assigned to IAM results, but can also help to identify those parameters for which a better knowledge can most improve the accuracy and precision of the overall results.

For estimates of ecosystems protection the spread of critical loads within a grid cell appears to have stronger impact on the resulting uncertainties and possible error compensation (as long as perfect correlation is assumed). This means in cases where countries report only few critical loads for grid cells or where these critical loads are in a similar range, estimates of ecosystems protection are rather uncertain since, e.g., a small change in these data or in deposition might change the protection status for many ecosystems.

Furthermore, it is important to point out that the traditional deterministic calculations of the RAINS model represent the median of the probability distribution and thereby assume a 50 percent probability of the achievement of the environmental targets. It is clear from the calculations that there is a significant uncertainty interval around the median and, depending on the level of confidence one puts into the calculations, the achievement of the original policy target appears in a different light.

As a conclusion, setting of interim or long-term environmental policy targets should not only address the desired level of protection but at the same time also consider the certainty with which this level should be achieved. As shown above the uncertainty range is considerable, and it needs to be explored how different confidence levels will influence the economic efforts that are needed to attain them.

5.5 Conclusions

A methodology to propagate uncertainties in model parameters through the calculation chain of the RAINS integrated assessment model is now available. Initial uncertainty analyses highlight the potential for error compensation, so that in many cases calculation model results are more certain than some of the input parameters.

Most of the methodological improvements considered desirable in Suutari *et al.* (2001a,b) have been achieved. Although there is room for technical improvements, basic tools and methods for uncertainty analyses under the LRTAP Convention are available. It is now up to the Parties not only to call for such analyses, but also provide the national data necessary for the execution of these analyses.

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7 Annex: Relevant Parts from Statistical Textbooks

All the statistical calculations are based on expected values. For example the mean of the random variables is the expected value of the variable, variance is the expected squared difference between a random variable and its expected value. If we have a random variable χ that has a continuous probability distribution $f(\chi)$ the expected value of χ is

$$\mathrm{E}[\chi] = \int_{-\infty}^{\infty} \chi\, f(\chi)\, \mathrm{d}\chi \qquad (1)$$

The following rules of expectations can be proved with the equation (1). Let χ and ψ be random variables and c be any number, then:

1. $\mathbf{E}[c] = c$
2. $\mathbf{E}[c\chi] = c\mathbf{E}[\chi]$
3. $\mathbf{E}[\chi + \psi] = \mathbf{E}[\chi] + \mathbf{E}[\psi]$
4. $\mathbf{E}[\chi\psi] = \mathbf{E}[\chi]\mathbf{E}[\psi]$, if χ and ψ are independent (2)

The following rules of variation can be proved with the above rules (2). Let χ and ψ be random variables and c be any number, then:

1. $\mathbf{Var}[c] = 0$
2. $\mathbf{Var}[c\chi] = c^2\mathbf{Var}[\chi]$
3. $\mathbf{Var}[\chi + \psi] = \mathbf{Var}[\chi] + \mathbf{Var}[\psi] + 2\,\mathbf{Cov}[\chi, \psi]$
4. $\mathbf{Var}[\chi\psi] = \mathbf{Var}[\chi]\mathbf{E}[\psi]^2 + \mathbf{Var}[\psi]\mathbf{E}[\chi]^2 + \mathbf{Var}[\chi]\mathbf{Var}[\psi]$, if χ and ψ are independent

The method for estimating the uncertainty of the integrated acidification model is based on the definitions of variance, covariance and Pearson coefficient of correlation:

1. Definition of variance:

$$\mathbf{Var}[\chi] = \mathbf{E}[(\chi - \mathbf{E}[\chi])^2] = \mathbf{E}[\chi^2] - \mathbf{E}[\chi]^2 \equiv \sigma_\chi^2$$

2. Definition of covariance:

$$\mathbf{Cov}[\chi, \psi] = \mathbf{E}[(\chi - \mathbf{E}[\chi])(\psi - \mathbf{E}[\psi])] = \mathbf{E}[\chi\psi] - \mathbf{E}[\chi]\mathbf{E}[\psi] \qquad (3)$$

3. Definition of coefficient of correlation:

$$\rho_{\chi\psi} = \frac{\mathbf{Cov}[\chi, \psi]}{\sqrt{\mathbf{Var}[\chi]\mathbf{Var}[\psi]}} = \frac{\mathbf{Cov}[\chi, \psi]}{\sigma_\chi \sigma_\psi}$$

We can notice that the covariance of variable itself is the variance of the variable

$$\mathbf{Cov}[\chi,\chi] = \mathbf{E}[\chi^2] - \mathbf{E}[\chi]^2 = \mathbf{Var}[\chi] \tag{4}$$

For the uncertainty calculations we estimate the standard deviations (square root of the variation) and the correlation coefficients of the model parameters. In the uncertainty calculations we present the uncertainty as a factor of the model parameter. If the model parameter is assumed to be unbiased the uncertainty factor has expected value one.

To demonstrate how the main equations in the following methods have been derived we study simple sums

$$\sum_i a_i \chi_i b_i \psi_i \quad \text{and} \quad \sum_p a_p \chi_p b_p \psi_p$$

where *a* and *b* are constants and χ and ψ are random variables (uncertainty factors for a and b) with expected value one. It is necessary to assume that χ and ψ random variables are independent. χ_i and χ_p can be correlated as well as ψ_i and ψ_p for any *i* and *p*. Then the expected value of the sum is

$$\mathbf{E}[\sum_i a_i \chi_i b_i \psi_i] = \sum_i a_i b_i \mathbf{E}[\chi_i]\mathbf{E}[\psi_i] = \sum_i a_i b_i \tag{5}$$

The covariance between two such sums is

$$\begin{aligned}
&\mathbf{Cov}[\sum_i a_i \chi_i b_i \psi_i, \sum_p a_p \chi_p b_p \psi_p] \\
&= \mathbf{E}[\sum_i a_i \chi_i b_i \psi_i \sum_p a_p \chi_p b_p \psi_p] - \mathbf{E}[\sum_i a_i \chi_i b_i \psi_i]\mathbf{E}[\sum_p a_p \chi_p b_p \psi_p] \\
&= \mathbf{E}[\sum_i \sum_p a_i \chi_i b_i \psi_i a_p \chi_p b_p \psi_p] - \sum_i a_i b_i \mathbf{E}[\chi_i]\mathbf{E}[\psi_i] \sum_p a_p b_p \mathbf{E}[\chi_p]\mathbf{E}[\psi_p] \\
&= \sum_i \sum_p a_i a_p b_i b_p \mathbf{E}[\chi_i \chi_p]\mathbf{E}[\psi_i \psi_p] - \sum_i \sum_p a_i a_p b_i b_p
\end{aligned} \tag{6}$$

To solve the covariance we have defined the expected value of a product of two random variables. For that we use the definitions of covariance and coefficient of correlation (definitions 3). From the definitions we derive the equation

$$\begin{aligned}
&\sigma_{\chi_i} \sigma_{\chi_p} \rho_{\chi_i \chi_p} = \mathbf{E}[\chi_i \chi_{pi}] - \mathbf{E}[\chi_i]\mathbf{E}\chi_p] = \mathbf{E}[\chi_i \chi_{pi}] - 1 \\
&\Leftrightarrow \mathbf{E}[\chi_i \chi_{pi}] = \sigma_{\chi_i} \sigma_{\chi_p} \rho_{\chi_i \chi_p} + 1
\end{aligned} \tag{7}$$