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Estimation of country contributions to the climate change

Viewpoints of radiative forcing and uncertainty of emissions

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VTT Processes

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Abstract

Global warming that occurs due to emissions from a country or a country group was studied from two different points of view. Firstly, warming effect caused by Finnish emissions from 1900 to 2100 was assessed using a model that describes removal of greenhouse gases from the atmosphere by pulse response functions, and calculates the radiative forcing caused by an increase in atmospheric concentration. Secondly, Finland's share of global emissions was assessed for the time period during which detailed greenhouse gas inventories were available, i.e. from 1990 to 2003, taking into account uncertainties in emission estimates. The uncertainty estimate was made using literature, measurement data and expert judgement on input parameter uncertainties. Stochastic simulation was used to combine the uncertainties. In addition, uncertainties in different emissions trading schemes were compared at EU level. Greenhouse gases covered by the study were those included in the Kyoto Protocol, i.e. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6). Sectors covered were energy, industry, transportation, agriculture and waste. LULUCF sectors (land-use, land use change and forestry) were covered more superficially.

Finnish greenhouse gas emissions in 2003 were 86 Tg CO_2 eq (without LULUCF). According to the results, 95% confidence interval of this figure lies between 82 and 92 Tg CO_2 eq. This represents a share of 0.2–0.3% of global emissions. In the same year, Finland's share of global population was 0.1% and share of global GDP 0.4%. The most important contributors to uncertainty were N_2O emissions from agricultural soils, N_2O from nitric acid production and CH_4 from landfills. Inclusion of LULUCF categories in the inventory increased relative uncertainty of net emissions notably (emissions in 2003 were 68 Tg CO_2 eq with a 95% confidence interval of 58 to 78 Tg CO_2 eq).

According to the radiative forcing calculations, forcing caused by Finland will increase from 3 mWm^{-2} in 1990 to 6–11 mWm^{-2} by 2100, depending on emission reduction strategies applied, and technological development. In 1990 Finland's share of global radiative forcing was estimated at 0.18% and by 2100 it will decrease to 0.13%, due to increase in global emissions. The results revealed that Finland's share of radiative forcing was smaller than the share of emissions. This was due to Finland's relatively short emission history.

It was concluded that uncertainty in EU emissions trading scheme for CO_2 (2005–2007) contains rather small uncertainties (±3% based on uncertainties in inventories), but the extension of emissions trading scheme to cover other sectors or gases is likely to increase the uncertainties (up to 21% in Kyoto emissions trading scheme).

Both radiative forcing and uncertainty assessment models developed in the thesis can be used in decision making, e.g. for comparing different emission reduction strategies and for planning of future climate commitments.

Preface

This thesis has been carried out as part of several research projects at the VTT Technical Research Centre of Finland. A large part of the work was carried out in connection with the official reporting of the Finnish Greenhouse Gas Inventory. These projects were funded by the Ministry of Trade and Industry and Statistics Finland, of which I wish to express my gratitude to Mirja Kosonen. The Ministry of the Environment financed projects that offered highly useful opportunities to interact with and learn from people working in the same field in other countries, of which my gratitude goes especially to Jaakko Ojala.

The first part of the work (radiative forcing model) as well as final stages were funded by VTT, of which I am grateful to Research Manager Kari Larjava, Group Manager Mikael Ohlström and former Research Manager Ritva Hirvonen (currently working at Energy Market Authority).

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My grateful appreciation goes to Paula Perälä and Dr Kristiina Regina of MTT Agrifood Research Finland for their co-operation both when preparing the first uncertainty estimates for agriculture and when writing the article included in the thesis. I would also like to thank the Greenhouse Gas Inventory compilers who lent their expertise for estimation of uncertainties: Kari Grönfors, Saku Slioor and Tuija Lapveteläinen from Statistics Finland, Kari Mäkelä at VTT Building and Transport and Jouko Petäjä of Finnish Environment Institute. I am especially grateful to Teemu Oinonen at Statistics Finland (formerly at Finnish Environment Institute) for fruitful co-operation.

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was invaluable. My warm thanks are also extended to the pre-examiners of the dissertation, Dr Wilfried Winiwarter from ARC Systems Research, Austria and Professor Jorma Jokiniemi from University of Kuopio. The pre-examiners provided valuable comments for improving the manuscript. I would also like to thank my godmother Sari Monni for checking the language and making the manuscript more readable.

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Finally, I want to thank my parents Aulikki and Aarne for their endless love and encouragement, and my sisters Satu and Outi for their invaluable background support. Last but not least, I would like to thank Juha for keeping me remembering the more important things in life.

List of publications

This thesis consists of the following original publications. Contribution of the author of this thesis is described below and in more detail in Chapter 7 of the thesis.

I. Monni, S., Korhonen, R. and Savolainen, I. 2003. Radiative forcing due to anthropogenic greenhouse gas emissions from Finland: methods for estimating forcing of a country or an activity. Environmental Management, Vol. 31, No. 3, pp. 401–411.

II. Monni, S., Syri, S. and Savolainen, I. 2004. Uncertainties in the Finnish greenhouse gas emission inventory. Environmental Science and Policy, Vol. 7, No. 2, pp. 87–98.

III. Monni, S., Syri, S., Pipatti, R. and Savolainen, I. 2004. Comparison of uncertainty in different emission trading schemes. In: Proceedings of the International Workshop on Uncertainty in Greenhouse Gas Inventories: Verification, Compliance and Trading. September 24–25, 2004, Warsaw, Poland. Pp. 106–115. [Extended version of Workshop paper is to be published in Water, Air & Soil Pollution: Focus (WAFO)]

IV. Monni, S., Perälä, P. and Regina, K. (In press.). Uncertainty in agricultural CH_4 and N_2O emissions from Finland – possibilities to increase accuracy in emission estimates. Mitigation and Adaptation Strategies for Global Change.

The author of this thesis was the responsible author of all the publications I–IV. For publication I, the author developed an updated version of the calculation model and was responsible for the model calculations and data acquisition. The author was responsible for sections describing methods, scenarios and results. The discussion and conclusions were written jointly with the co-authors.

In Articles II–IV, the author was responsible for development of the uncertainty calculation models, data collection and the calculation of results. In Articles II–III, the author wrote all chapters except the introductions, discussions and conclusions that were written jointly with the co-authors. In Article IV, the author was responsible for Sections 1, 2 (except Section 2.1 and the text on N_2O from agricultural soils in Section 2.4), and 3. Chapter 4 was written jointly with the co-authors.

Contents

Appendices I, II and IV of this publication are not included in the PDF version. Please order the printed version to get the complete publication (http://www.vtt.fi/inf/pdf/)

List of symbols

°C	degrees Celsius
A	gas-specific constant for radiative forcing of an F-gas
a	coefficient of pulse-response function of CO_2
α	factor describing the probability that the parameter value is outside the confidence interval
c	atmospheric concentration of a GHG (c_0 denotes undisturbed concentration)
C	atmospheric concentration of carbon dioxide (C_0 denotes undisturbed concentration)
COV	covariance
E_b	GHG emissions or removals in the base year (mean value)
E_t	GHG emissions or removals in the inventory year (mean value)
F	radiative forcing
f	pulse response function
L_1, L_2	lower and upper bounds of the 95% confidence interval
M	atmospheric concentration of methane (M_0 denotes undisturbed concentration)
N	atmospheric concentration of nitrous oxide (N_0 denotes undisturbed concentration)
ρ	Pearson's correlation coefficient
σ	standard deviation
t	time
τ	atmospheric lifetime for CH_4, N_2O, HFC, PFC or SF_6
τ_i	relaxation time (used in REFUGE2 for CO_2)
$trend_{b,t}$	change in net emissions from base year to the latest inventory year relative to the emissions in base year
U_+	upper bound of 95% confidence interval expressed as percent relative to the mean value

U_-	lower bound of 95% confidence interval expressed as percent relative to the mean value
VAR	variance
X	concentration of an F-gas in the atmosphere (X_0 denotes undisturbed concentration)

List of abbreviations

A2	one of the SRES scenarios used in the REFUGE2 model
ACT	activity
B1	one of the SRES scenarios used in the REFUGE2 model
B2	one of the SRES scenarios used in the REFUGE2 model
BAU^C	scenario for Finland used in the REFUGE2 model
BC	black carbon
C	carbon
CDM	Clean Development Mechanism
CF_4	perfluoromethane
CFC	chlorofluorocarbon
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
CO_2 eq	carbon dioxide equivalent (amount of emission in CO_2 equivalents is obtained when emissions are multiplied by the GWP value of the gas)
COP	Conference of the Parties to the UNFCCC
CRF	common reporting format (used in reporting to the UNFCCC)
EF	emission factor
EIT	economies in transition
ET	Emissions Trading
EU	European Union
EU-15	member states of the European Union before May, 2004
EU-25	member states of the European Union since May, 2004
EU ETS	emissions trading scheme of the EU (2005–2007)
F-gas	fluorinated gas (HFCs, PFCs and SF_6)
FCA	Full Carbon Account (of forests)

FIN	Finland
FOD	first order decay method
GDP	gross domestic product
GLOB	global
H_2O	water vapour
HCFC	hydro-chlorofluorocarbon
HFC	hydro-fluorocarbon
GHG	greenhouse gas
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
JI	Joint Implementation
KASPER	model for the calculation of uncertainty in greenhouse gas emissions developed in this thesis
$KIO1^C$	scenario for Finland used in the REFUGE2 model
LCA	life cycle assessment
LHS	Latin Hypercube simulation
LULUCF	land use, land use change and forestry
MC	Monte Carlo simulation
N	nitrogen
N_2O	nitrous oxide
NIR	National Inventory Report (reporting to the UNFCCC)
NMVOC	non-methane volatile organic compounds
NO_X	nitrogen oxide
O_3	ozone
OC	organic carbon
OH	hydroxyl radical
PDF	probability density function
PFC	perfluorocarbon
REFUGE2	model for calculation of radiative fording developed in this thesis
RF	radiative forcing

SF_6	sulphur hexafluoride
SO_2	sulphur dioxide
SRES	Special Report on Emission Scenarios (by IPCC)
$Techno^C$	scenario for Finland used in the REFUGE2 model
UNFCCC	United Nations Framework Convention on Climate Change
VOC	volatile organic compounds
yr	year

1. Introduction

1.1 Global warming

It is estimated that climate change, or global warming, occurs when human activity causes an increase in atmospheric greenhouse gas concentrations. Natural greenhouse effect – caused mainly by atmospheric H_2O and CO_2 – is a vital requirement for life on Earth as we know it. Human activities, e.g. combustion of fossil fuels, certain farming practices and management of wastes cause greenhouse gas emissions, resulting in an increase in greenhouse effect. This increase is leading to climate change. [IPCC 2001a]. Climate change is a global phenomenon, because greenhouse gases are mixed in the whole atmosphere and because ocean currents and atmospheric flows transfer energy globally. Therefore, development of climate change depends heavily on global total emissions rather than on local or regional emissions.

Human perturbation on atmospheric GHG concentration is predicted to cause, e.g., increase in global mean temperature, sea level rise, and also, likely in frequency of extreme climatic events. According to IPCC, global mean temperature is expected to rise 1.4–5.8 °C by 2100 and the sea level 0.09–0.88 meters during the same time span. Climate change may have notable consequences on human life, especially in the poorest areas, due to effects on grain yields, drought and floods. [IPCC 2001b].

Anthropogenic emissions increase greenhouse gas concentrations in the atmosphere. Carbon dioxide (CO_2) is the main cause of human-induced global warming. The main source of carbon dioxide is the combustion of fossil fuels – coal, oil and natural gas. Some industrial processes, e.g. manufacturing of cement and lime, also cause CO_2 emissions. Land use activities, e.g. cutting of forests, cultivation of soils and management of peatlands, cause changes in carbon stocks. The activities related to land-use and forestry may cause either emissions or removals of carbon dioxide. CO_2 emission occurs, when, e.g., cutting of forests exceeds annual growth. However, certain management practices of, e.g. forests or cultivated land, cause removals by increasing the carbon stocks.

Methane (CH_4) has several natural sources, of which wetlands are the most important. IPCC estimates that 60% of annual global CH_4 emissions are caused by human activity. The most important anthropogenic emission sources are waste management (landfills), enteric fermentation of ruminants, rice cultivation and fuel combustion. Soils can act both as sinks and sources of methane. [IPCC 2001a].

Majority of anthropogenic nitrous oxide (N_2O) emissions come from agricultural soils, due to, e.g. nitrogen fertilisation. In addition, some industrial sources (e.g. nitric acid and adipic acid production), manure management and fuel combustion cause N_2O emissions. [IPCC 2001a].

HFCs, PFCs and SF_6 are mainly of anthropogenic origin, and they are released by various industrial processes and by use of these gases in different products, like in refrigeration and air conditioning equipment. [IPCC 2001a].

Greenhouse gases are removed from the atmosphere in various ways and time scales. CO_2 circulates between the atmosphere, the oceans and the terrestrial biosphere. CH_4 and HFCs are primarily removed from the atmosphere by reactions with hydroxyl radical (OH), but methane is also absorbed to some extent by aerobic soils. Some greenhouse gases are removed from the atmosphere by photodissociation, for example N_2O, PFCs and SF_6. [IPCC 2001a].

Lifetime of greenhouse gases in the atmosphere varies from around 1.4 years of HFC-152a to over 50 000 years of perfluoromethane (CF_4). Global warming effect of greenhouse gases depends, in addition to their lifetimes, on radiative properties of these gases. Warming effect can be measured by radiative forcing which is defined as the perturbation to the net irradiance at the tropopause after allowing the stratospheric temperature to re-adjust to radiative equilibrium [IPCC 2001a]. Radiative forcing can be used as an index when estimating greenhouse impact caused by, e.g. global or regional emissions or emissions from a single country or an activity.

Human-induced global warming is a complex phenomenon, and the direct greenhouse gases of the Kyoto Protocol (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) are the most important cause of it. However, there are various other issues

affecting global warming, for example changes in planetary albedo (caused by, e.g. land-use change), changes of solar irradiance and stratospheric aerosols from volcanic eruptions, aerosols/aerosol precursors (BC, OC and SO_2), loss of stratospheric O_3 and increase in tropospheric O_3 (caused by, e.g. CO, NMVOC and NO_X). In addition, the emissions of direct greenhouse gases CFCs and HCFCs controlled by the Montreal Protocol have large global warming potentials. [IPCC 2001a; Rypdal et al. 2005].

Mitigation of climate change is affected by different types of inertia. For example, the removal of excess CO_2 emissions from the atmosphere is slow, and the oceans' thermal capacity lowers the warming rate. Because response times are long, mitigation of climate change would require significant reductions of greenhouse gas emissions. Reduction of greenhouse gas emissions is complicated due to several issues, such as limitations of current scientific knowledge and technology as well as socioeconomic inertia including population, governance, investment stock and consumption patterns.

1.2 Mitigation of climate change by international commitments

Anthropogenic climate change was seen as a considerable problem, which in the late 1980's resulted in international negotiations to mitigate this threat. In 1992 in Rio de Janeiro, the United Nations Framework Convention on Climate Change (UNFCCC) was agreed, which was seen as the first step towards global mitigation of climate change. Parties of the UNFCCC agreed on stabilisation of GHG concentrations in the atmosphere at a non-dangerous level. In 1997, first quantitative emission reduction targets were set to industrialised countries (Parties listed in Annex I of the Protocol), when the Kyoto Protocol was adopted in the Third Conference of Parties (COP3) to the UNFCCC in Kyoto. [UN 1992; FCCC 1997]. According to commitments in the Kyoto Protocol, industrial countries should reduce greenhouse gas emissions on average by 5% from the 1990 level during the first commitment period 2008–2012. Greenhouse gases covered by the Kyoto Protocol are CO_2, CH_4, N_2O, HFCs, PFCs and SF_6.

Kyoto Protocol entered into force eight years later, in February 2005. The current emission reduction target is not enough to stabilise atmospheric

greenhouse gas concentrations, but it is a beginning of the emission reduction process. Some industrial countries, including USA, did not ratify the Kyoto Protocol and therefore they did not join to emission reduction commitments.

UNFCCC and the Kyoto Protocol cover energy, industrial processes, product use, agriculture, and waste sectors. Furthermore, greenhouse gas emissions and removals from land-use, land-use change and forestry categories are to be reported. Under the Kyoto Protocol, only a part of a country's total removals can be credited according to Articles 3.3 and 3.4. Article 3.3 covers afforestation, reforestation and deforestation, and article 3.4 covers revegetation, forest management, cropland management and grazing land management. In addition, it was decided that Parties have to report changes in carbon pools above- and below-ground biomass, litter, soil organic carbon and dead wood. Accounting for a given pool is not necessary during the commitment period, if it can be shown that a pool is not a net source. [FCCC 2001].

In the Kyoto Protocol, three mechanisms are implemented, with which the Annex I Parties can cut the cost of meeting emission reduction targets by reducing emissions or increasing removals in other countries, where it is more cost-efficient. The three available mechanisms are: Emissions Trading (ET), Joint Implementation (JI) and Clean Development Mechanism (CDM), the rules of which are defined in the Marrakesh Accords [FCCC 2002]. Under Emissions Trading, emissions are traded between Annex I Parties. In Joint Implementation, Annex I Party implements an emission reduction project in another Annex I Party. It is estimated that JI projects will mainly be implemented in EIT countries (economies in transition) where cost-effective emission reduction projects are likely to be available. Under Clean Development Mechanism, Annex I Party may conduct an emission reduction project in a non-Annex I Party, and use emission reductions achieved when meeting its own target. Under the mechanisms, the reduction in emissions and the increase in sinks are treated similarly in principle, but there are more restrictions for the use of sinks due to their uncertainties and possible interim character. [FCCC 2002; FCCC 2004a].

The European Union (EU-15) has formed a bubble under the Kyoto Protocol, where EU countries have a common emission reduction target of -8% from the 1990 level. Under the burden sharing of the EU, Finland's target was set to 0%, i.e. to freezing of emission to the 1990 level.

As a measure for reaching the Kyoto emission reduction commitments cost-efficiently the European Union, including both old and new member states (EU-25), started the CO_2 emissions trading in the beginning of 2005. The EU ETS includes CO_2 from combustion and selected industrial processes in large installations. EU is planning to extend the emissions trading scheme after the first phase (2005–2007). [Official Journal of the European Union 2003].

Under the Kyoto Protocol, emissions of different gases are weighted according to their 100-year GWP values that represent warming effects of different gases compared with the warming effect of CO_2. The GWP approach is a simple and practical means for summing up the emission of different gases. However, this approach does not cover historical emissions and it does not explicitly take into account the slow removal of greenhouse gases from the atmosphere leading to accumulation of gases. Radiative forcing approach (used e.g. in Article I of this thesis), gives an index that takes also these effects into account.

Negotiations on the second commitment period after the Kyoto period (2008–2012) should begin in 2005. There are various proposals concerning extensions of the Kyoto Protocol, for example emission reduction commitments in developing countries and inclusion of other gases than those mentioned in the Kyoto Protocol [Rypdal et al. 2005].

1.3 Uncertainties in estimation of climate change

Uncertainty is an unavoidable part of practically all scientific data. Estimation of greenhouse gas emissions or removals contains uncertainties, since not all relevant processes are understood to the full. For example, there may be a notable lack of relevant data or the estimation methods may be biased. When estimates are extended to atmospheric greenhouse gas concentrations, radiative forcing or global warming caused by a single country, the studied phenomena are more complex and the number of uncertain components increases.

1.3.1 Uncertainties in estimates of emissions and removals

The estimates of global annual emissions can be based on atmospheric measurements. In the case of some gases, it is difficult to distinguish between natural and anthropogenic sources. The IPCC estimated that average annual CO_2 emission in the 90's was 6.3 ±0.8[1] PgC/yr from combustion of fossil fuels and production of cement. Emissions and removals from LULUCF sector are more difficult to estimate; globally, the annual average CO_2 emissions from LULUCF were estimated to range from 1.6 ±1.6 PgC/yr [IPCC 2001a], corresponding to uncertainty of ±100% (95% confidence interval). Emission generating processes in the LULUCF sector are complex, and it is especially difficult to assess which part of the emissions or removals is caused by human activity, and which is natural. In addition, monitoring of emissions or removals is very expensive. [Gupta et al. 2003].

For methane, total atmospheric burden can be assessed rather accurately (±10%), but estimation of annual emissions is more difficult. Emissions from anthropogenic and natural sources are nearly equal, and therefore, uncertainties in the estimates of human-induced increase in the atmospheric concentration are high. Estimates of annual anthropogenic N_2O emissions vary from 1.3 to 20.7 TgN/yr [IPCC 2001a, Table 4.4]. F-gases (HFCs, PFCs and SF_6) do not have any notable natural sources, which means that global emissions can be rather accurately estimated based on atmospheric measurements.

Even though atmospheric measurements are useful for the estimation of global emissions, emissions from each country have to be estimated by calculations, e.g. by compiling annual emission inventories. In 1999, uncertainty estimation was included in the reporting requirements of the UNFCCC [FCCC 1999]. From 2004 onwards [FCCC 2003], uncertainty estimates have to be prepared based on the IPCC Good Practice Guidance [IPCC 2000a].

It is estimated that uncertainties in annual inventories of greenhouse gases in Annex I countries of the Kyoto Protocol vary from ±4 to ±20% (upper and lower

[1] In IPCC [2001a] error ranges were presented as ±σ, but for the sake of consistency they are converted to ±2σ (corresponding roughly to 95% confidence interval for normal distribution) in this thesis.

bounds of the 95% confidence interval expressed as percent relative to the mean value), while uncertainties in the LULUCF sector are not covered [Rypdal & Winiwarter 2001]. The emissions of CO_2 are the typically best known, followed by methane. Uncertainty estimates for N_2O, HFCs, PFCs and SF_6 range widely between different countries. In general, energy and industrial processes sectors are better known than waste and agriculture sectors. Differences in uncertainty estimates by gas and by sector in different countries are also discussed in Article III, and comparison between different countries is presented in Table 5 in Article II. The issue is also covered in Section 4.2.4 of the thesis.

In the Kyoto Protocol, commitments are presented as emission reductions relative to the base year. Therefore, uncertainties in emission trend (change in emissions between inventory year and the base year) become interesting. A study by Rypdal & Winiwarter [2001] revealed that trend uncertainties were rather similar for different Annex I countries, ±4–5 percentage points without LULUCF. The results presented for Finland in Article II are in the same range. Trend uncertainties are discussed in more detail in Chapter 3 and Section 4.2.4.

Uncertainty estimates of emissions or removals from LULUCF sector are scarce. Some uncertainty studies of different models presenting carbon stock changes in forests or soils have been published [Paul et al. 2003a, b; Smith & Heat 2001; Heat & Smith 2000; Zhang & Xu 2003; Nilsson et al. 2000, Ogle et al. 2003; Vandenbygaard et al. 2004]. However, they are not fully applicable for the estimation of uncertainties in GHG inventories, particularly because the GHG inventories are compiled annually, whereas the studies mentioned above mainly concentrate on longer time periods. In the LULUCF sector, uncertainties in annual estimates may be substantially different from uncertainties in averages over longer time periods. IPCC published Good Practice Guidance for Land use, Land-Use Change and Forestry in 2004 [IPCC 2003]. This guidance formed a basis for the estimation of emissions and removals from land-use activities, and also a basis for the estimation of uncertainties in LULUCF sector. From 2005 onwards, the Parties have had the obligation to estimate uncertainties in LULUCF according to the IPCC [2003] guidelines [FCCC 2004b]. Chapter 3 of this thesis presents tentative results for the estimation of uncertainties in the LULUCF sector in Finland.

Even though reporting of uncertainties is required, no limits for uncertainty of emissions or emission reductions are given in the Kyoto Protocol or subsequent rules of the Kyoto Protocol. However, implications of uncertainty in climate policy have been discussed in scientific literature.

Gupta et al. [2003] discussed implications of uncertainty in compliance with the Kyoto Protocol. They concentrated on implications of uncertainty on environmental effectiveness of the UNFCCC and how uncertainty affects the legal enforcement of the protocols. They proposed a minimum requirement for the probability of compliance with emission reduction targets. In addition to reducing emissions, this suggestion gives an incentive to reduce uncertainties as well. They also mentioned that reduction of uncertainty always carries a cost, and therefore, due to economic restrictions, certain amount of uncertainty is inevitable. They claimed that because reduction of CH_4 and N_2O is often more cost-effective than reduction of CO_2, Parties may be in favour of reducing emissions in more uncertain categories, when uncertainty in emission reductions is not restricted.

Gillenwater et al. [2004] proposed that emission estimates of Parties could be adjusted based on corresponding uncertainties. To be able to calculate adjusted emissions, a certain confidence level for emission reductions should be agreed. However, it was concluded that the use of potentially non-comparable uncertainty estimates for the adjustment of emissions would be questionable. Uncertainty estimates provided by Parties are difficult to compare, and uncertainties in uncertainty estimates may be even larger than uncertainties in emission estimates.

Emissions trading gives monetary value to emissions. Therefore, it will be of interest, how accurately the quantities sold are known. This was taken into account in the Guidelines for Monitoring prepared for EU emissions trading [EC 2004], when limits for activity data uncertainties were set. Possibilities to apply boundaries for uncertainties in emissions trading have been studied by Nahorski et al. [2004] and Horabik & Nahorski [2004]. Uncertainties involved in different EU emissions trading schemes were also discussed in Article III of this thesis.

Estimates of uncertainty in JI and CDM projects have been presented by Parkinson et al. [2001] and Gupta et al. [2003]. In JI and CDM, an estimate is

made concerning future emissions from a particular source, and this forecast is used as a baseline for the project. Uncertainty involved in the forecast forms one source of uncertainty in JI and CDM projects [Parkinson et al. 2001; Gupta et al. 2003]. Another form of uncertainty arises when the achieved emission reductions are estimated. These uncertainties are comparable to those in emission inventories. [Gupta et al. 2003]. Jotzo & Michaelowa [2002] have estimated that CDM market will be small during the first Kyoto period, and thus the effect of these uncertainties will be small as far as total uncertainty of emission reductions achieved under the Kyoto Protocol is concerned.

Future emission reduction commitments may cover a wider range of countries and gases than the Kyoto Protocol. Currently, nearly all studies concerning GHG emission uncertainties have been conducted in developed countries (except e.g. a study by Kumar et al. [2004]). In developing countries, the activity data uncertainty is potentially more important than in developed countries. In addition, many parameters used to calculate emissions in accordance with the IPCC guidelines are based on data from industrialised countries, and they might be unsuitable for developing countries.

Rypdal et al. [2005] discussed the possibility of including more gases to future protocols by comparing uncertainties of different gases. They argued that uncertainty ranges for emission estimates of SO_2, NO_x and NMVOC vary from ±4 to 23%, and therefore their inventories are not more uncertain than those of direct GHGs. It is estimated that uncertainties in CO inventories are greater, but could possibly be reduced with better reporting. Uncertainties in BC and OC inventories are very high. On the one hand, it is important to include the most important contributors to the forthcoming protocols, but on the other hand, emissions included in the protocols should be known accurately enough in order to ensure the real environmental benefits of emission reduction commitments.

Climatic effect of different gases varies, and it is therefore challenging to prepare indexes with which effects of different gases can be summed up. Even in the case of direct GHGs of the Kyoto Protocol, the GWP approach chosen has notable weaknesses that introduce additional uncertainty in CO_2 equivalent emission estimates [Reilly et al. 1999]. According to the IPCC [2001a], uncertainties in direct GWPs are around ±70% (2σ) for well-mixed greenhouse gases CH_4, N_2O, HFCs, PFCs and SF_6 (for CO_2 the GWP value is 1 according to

the definition). For SO_2, NO_x and NMVOC the GWP values depend on the location of emissions and are more uncertain than those of direct GHGs.

Above, the discussion of uncertainties in greenhouse gas emissions has mainly concentrated on current emissions. However, information on historical conditions is also important, e.g., for models describing soil carbon stocks and waste degradation in landfills. Information on the reliability of emission estimates of the past are also needed if one is interested in reliability of radiative forcing calculations. Retroactively gathered data (often interpolated or extrapolated using assumptions) are likely to contain larger uncertainties than data from the most recent years.

1.3.2 Uncertainties in global warming estimates

Estimation of radiative forcing and global warming needs the assessment of the non-linear features of climate change and therefore, sources of uncertainty are more complex than in emission estimates. When estimating radiative forcing caused by a single country or an activity, uncertainties in RF add up to uncertainties in emissions described in Section 1.3.1. However, on global scale, measurements of atmospheric concentration contain relatively small uncertainties.

All gases covered in this thesis (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) are well-mixed in the atmosphere. They have long lifetimes and nearly uniform spatial distribution. In consequence it is possible to yield rather accurate estimates of their radiative forcing due to a particular concentration, based on a few observations. It is estimated that the radiative forcing due to all well-mixed greenhouse gases since pre-industrial times is 2.43 Wm^{-2} with an uncertainty of ±20% (the uncertainty estimate is based on the range of model results and the discussion of different factors contributing to uncertainties). [IPCC 2001a].

For short-lived species such as aerosols, observations have to cover longer time periods and wider spatial regions. These kinds of observations are not yet in place. Therefore, estimation of radiative forcing of these species is more uncertain. [IPCC 2001a]. For example, uncertainties for direct radiative forcing of BC and OC are estimated to range from factor of 2 to factor of 3 (expressed as

one standard deviation, corresponding to factor of 4–6 for 2σ). [Rypdal et al. 2005; IPCC 2001a]. Figure 1 presents global mean radiative forcing due to different agents with corresponding estimates of uncertainty. Some RF agents (e.g. direct GHGs) are well mixed over the globe, whereas some (for example aerosols) have a more regional effect. Solar variation is the only factor that is not affected by human activity [IPCC 2001a].

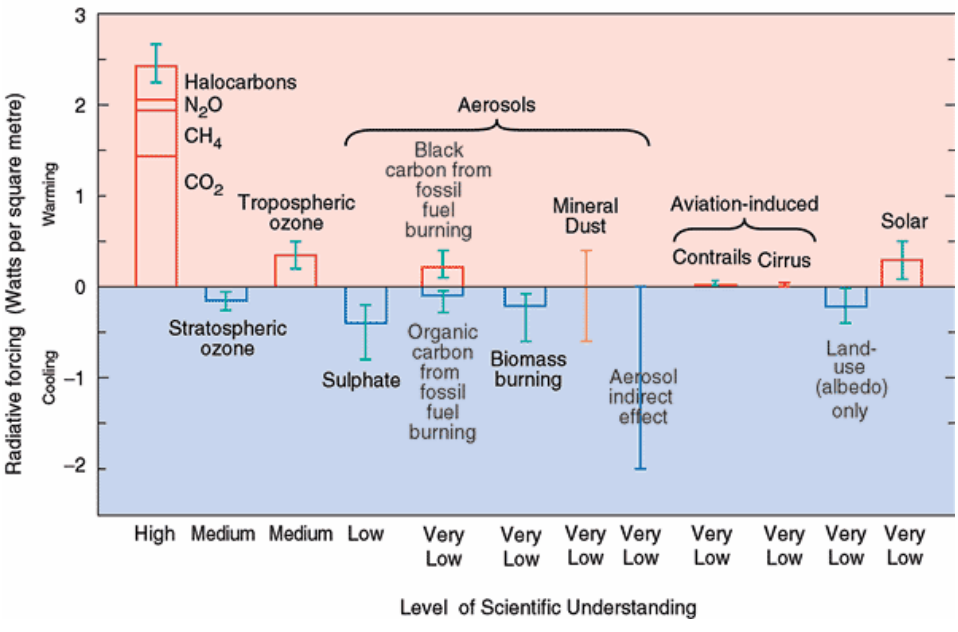

Figure 1. The global mean radiative forcing for the year 2000, relative to the year 1750 due to different agents. Vertical lines indicate the possible range of radiative forcing, estimated based on physical understanding and on a range of estimates presented in the literature. For aerosol indirect effect and mineral dust only a range is given, because it was not possible to give a best estimate. Level of scientific understanding is also verbally estimated below each column [IPCC 2001a].

When estimating global warming caused by anthropogenic emissions, one of the most challenging tasks is the estimation of climate sensitivity parameter that describes global mean surface temperature response to radiative forcing. A more detailed discussion on climate sensitivity is beyond the scope of this thesis, but Figure 2 gives an overview of related uncertainties.

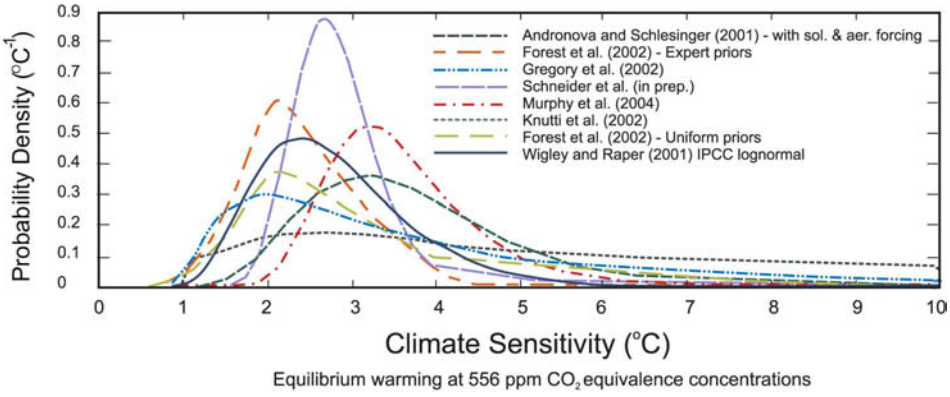

Figure 2. Probability density functions of global mean temperature rise for one particular CO_2 equivalence concentration level (556 ppm) at equilibrium according to different models. [Den Elzen & Meinshausen 2004].

Figure 2 presents a wide range of possible increase in global mean temperature for a particular CO_2 equivalence concentration at equilibrium. In reality, if future climate is to be predicted, also the uncertainty in future concentration has to be estimated. Figure 3 presents a possible range for temperature rise from 1900 to 2100. It is based on scenarios presented in the IPCC Special Report on Emission Scenarios [IPCC 2000b]. The range shaded with dark blue represents differences in emission estimates (scenarios) of GHGs and particular matter. The area presented in light blue describes the differences between different climate models. However, it has to be noted that the range of temperature rise is narrower than that in Figure 2, which presented temperature rise for one particular concentration only, but on the other hand, equilibrium is not assumed to be reached in Figure 2. Real uncertainty in future temperature rise may be even larger than in Figure 2 and Figure 3, if both uncertainty in future emissions and uncertainty in climate sensitivity are taken into account.

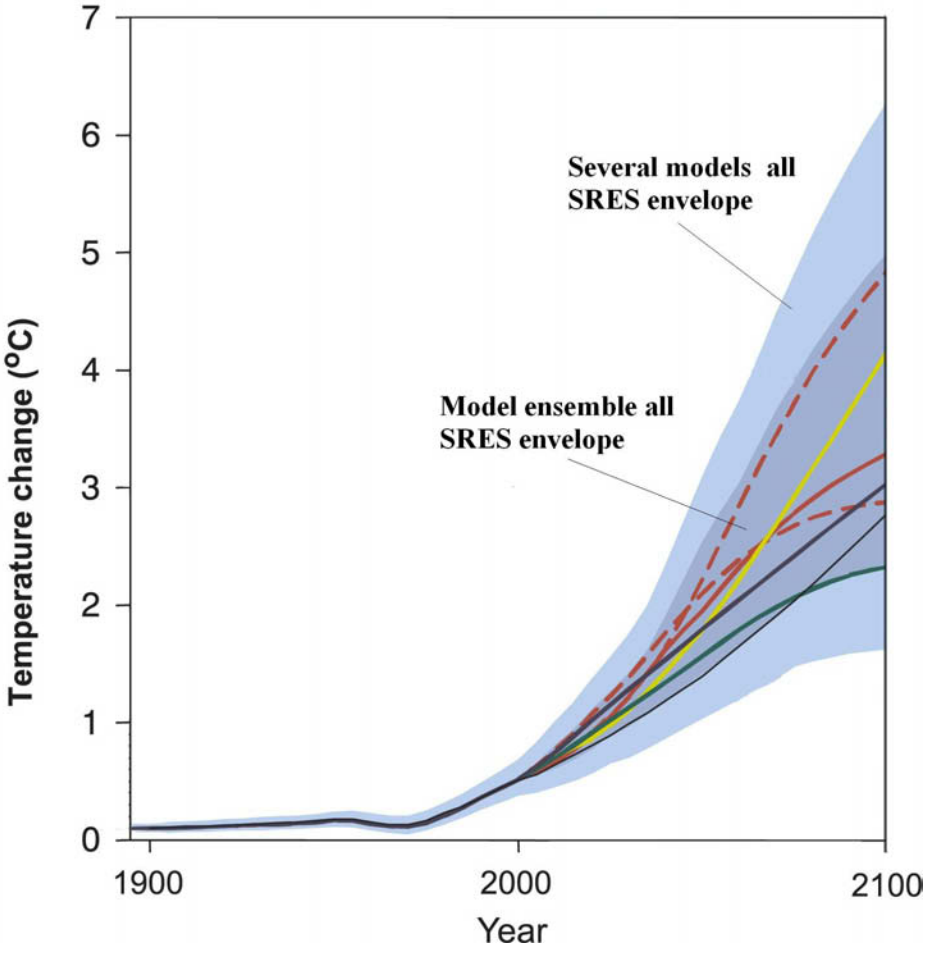

Figure 3. Possible range of temperature rise in different emission scenarios and calculated with different models [IPCC 2001a]. The range shaded with dark blue represents differences in emission estimates (scenarios) of GHGs and particular matter. The area presented in light blue denotes the differences between different climate models.

1.4 Methods to estimate uncertainties

Estimation of uncertainty can be divided into three steps: 1) identification of different sources of uncertainties 2) quantification of uncertainties 3) combining of uncertainties to get the final result – uncertainty in quantity of interest.

There are different types of uncertainty, due to, e.g., the characteristics of the emission source or the method used to estimate emissions. For example, Gillenwater et al. [2004] divided uncertainty in GHG inventories into two different types: 1) to scientific uncertainty that occurs because the science behind emission generating processes is not sufficiently well known and 2) to estimation uncertainty containing both model and parameter uncertainty.

Classification of uncertainty into different types varies [IPCC 2000a; Winiwarter & Rypdal 2001; Frey & Burmaster 1999; Rypdal & Zhang 2000; Li & Frey 2002]. Nevertheless, more important than the exact definitions of the types is the coverage of all possible sources of uncertainty. In Table 1, different types of uncertainty that may occur in the estimation of global warming are presented with examples. It is important to understand that many types of uncertainty are linked together. For example, lack of suitable data for modelling purposes may be interpreted both as model error and error in the representativeness of the data used.

Table 1. Different types of uncertainty with examples regarding estimation of global warming.

Type of uncertainty	**Examples**	**Random error**	**Bias**
Measurement error	human error, errors in calibration	x	x
Modelling error	oversimplification of modelling approach, errors in expert estimates of parameter values		x
Sampling error	number of data points taken (sample size) too small	x	x
Unrepresentativeness of the data	emission factors used for combustion are derived using data for power plants operating in full load only, parameters used in models to estimate emissions from soils are not suitable for all soil types		x
Natural variability of emission sources	use of long-term averages in models vs. emissions occurring in a specific year	x	x
Definitions and classification	misunderstanding of classifications used => double-counting or non-counting of emissions		x
Lack of coverage	incompleteness of emission inventory with regard to total anthropogenic emission (missing sources, processes etc)		x

First of all, uncertainty is often divided to bias and random error. Bias that is also called systematic error or inaccuracy, leads to deviation of data from its real value. Bias occurs, e.g. due to an inaccurate measuring method, lack of representativeness of data or unsatisfactory modelling of emission generating phenomena. Estimation of bias is difficult because if the magnitude of bias were known, it would generally be corrected before assessing uncertainty. In some cases, bias can be quantified by using expert judgements or data quality investigations [Gillenwater et al. 2004].

Random error, also called imprecision, is often due to a random measurement error or a statistical random sampling error [Li & Frey 2002]. Random error can be detected by repeating experiments or data sampling [Gillenwater et al. 2004]. In Table 1, different types of uncertainty are classified as random error and bias.

Uncertainty derives from a combination of all sources of bias and random error presented above. Thus, uncertainty describes the lack of knowledge of the real value of the quantity, regardless of the reason. Regarding the objective of this thesis, uncertainty can be described as aggregation of insufficiencies in estimation of a country's contribution to global warming.

Measuring is, in some cases (e.g. non-CO_2 gases from combustion), the most appropriate means to estimate emissions. It may include errors due to different reasons – e.g. errors in calibration or interpretation of results. In GHG inventories, most sources cannot be estimated by using direct measurements. Therefore, emissions are modelled using, e.g. activity data and emission factor values, or more complex models. In these cases, unrepresentativeness or lack of knowledge of emission factors, modelling errors, or bias in expert estimates may introduce uncertainty in model results. Complex emission forming process may be known incompletely, and therefore even the most complex models may be unable to describe the emission generating process in a sufficiently accurate manner. To give an example, in the case of N_2O emissions from agricultural soils, many countries have estimated very large uncertainties that are due to complexity of emission source, insufficient understanding of the influence of different factors on emissions and a lack of representative studies covering different soil types and climatic conditions [Rypdal & Zhang 2000; Winiwarter & Rypdal 2001; Oliver et al. 2003; IV]. When extending estimates from

emissions to the global warming effect, model uncertainty gets an even more central role.

In emission inventories, non-representative data is often used, when complete data sets are not available. A small amount of (unrepresentative) data may be used erroneously for upscaling, or data available only for few years may be extrapolated over a longer time-period even if there is no exact knowledge of the conditions during the years in question. Examples include modelling of waste degradation and carbon stock change in soils, where data is required from rather a long time for an estimate of current emissions.

Definitions and classification may be incomplete or misunderstood. For example, Nilsson et al. [2004] state that results of uncertainty estimates hold only within the model used, but e.g. completeness has to be estimated by other means. This is especially important when presenting estimates of total anthropogenic GHG emissions – lack of coverage of emission sources may introduce significant bias in the estimates.

Natural variability introduces uncertainty in the system when natural (but human-induced) emissions or removals are estimated annually, using parameters that are long term averages. Even though uncertainty in the average parameter may be small, its applicability to conditions in a given year may be poor, which in turn introduces bias the in estimates. This is typical for agriculture and LULUCF sectors.

In GHG inventories, the main interest is in national annual emissions. Therefore, it is important to differentiate between variability of population (e.g. the weights of cows) and uncertainty in the mean of the population. When populations are large, inter-unit variability is often much larger than the uncertainty of the mean [Frey & Zheng 2002]. Variability occurs due to differences in a quantity in a population, whereas uncertainty arises from lack of knowledge on the true value of the quantity. Variability cannot be reduced, but uncertainty can often be reduced with the help of the results of a further study (reduction of bias) or by using larger or more representative data sets (reducing random error) [Frey & Burmaster 1999]. However, if no representative sample is available, variability in a small sample may give insight in the possible uncertainty for the mean value. In these cases, even if the variability in the population is used as

uncertainty range, uncertainty may be underestimated if the sample is not representative, and a random sampling error occurs [Frey & Burmaster 1999].

When possible sources of uncertainty have been mapped, uncertainties have to be quantified (step 2). Literature surveys, examination of measurement results and expert judgements are common methods used for this purpose. Input parameter uncertainty can be described in a variety of ways, e.g. using fuzzy data sets, distributions obtained using bootstrapping and direct formulation of PDFs.

Fuzzy data sets or data quality indicators can be used if quantitative estimates of uncertainty cannot be produced, or the shape of the probability distribution cannot be known exactly. These approaches have been used in, for example, uncertainty analysis of Life Cycle Assessment (LCA) and climate-pest models [Maurice et al. 2000; Chevalier & Le Teno 1996; Weidema & Wesnaes 1996; Scherm 2000]. Maurice et al. [2000] combined both qualitative and quantitative estimates of uncertainty in the LCA of electricity production in coal power plants. The first step of their uncertainty assessment was based on the use of data quality indicators, because the determination of PDFs was considered problematic, different types of uncertainty were difficult to analyse and a compilation of full quantitative uncertainty assessment would have been too time consuming. Based on the analysis of the results of the first step, the quantitative assessment of most important data was done by defining the PDFs. Finally, uncertainties were combined using Monte Carlo simulation. Chevalier & Le Teno [1996] used fuzzy logic and stated that it is a more suitable means for describing uncertainty than PDFs, because PDFs can only model accurate data, and the generation of PDFs requires a lot more information than fuzzy numbers.

Scherm [2000] argued for the usage of fuzzy arithmetic for impact assessment of climate change, because it can give a 'worst-case' estimate when single errors cannot cancel each other out. He stated that Monte Carlo simulation methods are not suitable for the estimation of uncertainty in climate change impact assessment models, because precise details of PDFs and their dependencies are not available. Fuzzy logic was also favoured because of smaller need for computing time and capacity.

If qualitative assessment is used to estimate uncertainties, at one stage of the analysis data quality indicators have to be converted to numbers to combine uncertainties [Weidema & Wesnaes 1996; Maurice et al. 2000]. However, there is not enough evidence to prove that qualitative assessment by different experts reflects a certain probability range. On the contrary, linguistic imprecision may introduce a new source of uncertainty. Therefore, there are no valid reasons to believe that fuzzy set operations represent human reasoning with linguistic imprecision in a satisfactory manner. [Morgan and Henrion 1990, p. 61]. In addition, Nilsson et al. [2004], who stated that a full carbon account of forests (that could also be used in GHG inventories) is a typical fuzzy system, concluded that even though fuzzy logic is a part of a formal mathematical theory for the representation of uncertain systems, a comprehensive formal usage of fuzzy logic is not yet applicable in this area.

Bootstrap simulation can be used, if the exact form of probability density function is not known, and it can also be used for parametric PDFs. The main assumption of bootstrap simulation is that the observed values give the best estimate of the probability distribution of real data. Therefore, in Bootstrap simulation, sampling from an empirical data set is enabled. [Li & Frey 2002]. Bootstrap simulation can also produce estimates of confidence intervals even when an analytical solution is not available [Frey & Burmaster 1999]. In parametric Bootstrap simulation, synthetic data sets (Bootstrap samples) are taken from the population distribution using Monte Carlo technique. Therefore, bootstrap samples that have the same number of data points as the original data set are considered as a possible random realisation of the original data. [Li & Frey 2002]. Bootstrap simulation was used, for example, in the uncertainty assessment of GHG inventory of Norway [Rypdal & Zhang 2000].

In an uncertainty estimate of VOC emission factors, Li & Frey [2002] compared empirical distribution and fitting of parametric distribution to data. In their view, it is a limitation of any empirical PDF that it does not include extrapolation beyond the range of data observed. This may lead to an underestimation of uncertainty, whereas when parametric distribution is fitted to the data, also the unobserved tails of the distribution can be estimated, when there is sufficient theoretical background for the estimation of the distribution shape.

Uncertainties can also be described by using parametric PDFs. Firstly, parametric distributions can be fitted to empirical data. The fitted distributions can then be complemented with expert judgement about the quality of the data. If not enough representative data for distribution fitting is available, PDF can be selected by using the knowledge of basic characters of the parametric distributions. Normal distribution is used in statistics frequently, and it describes many natural occurrences well, e.g. the distribution of animal weights. The most likely value of normal distribution is the mean value, and probability of other values reduces when the distance to mean value increases. Furthermore, according to the Central Limit theorem, the sum of many uncertain quantities tends to be normal. Normal distribution is used quite often in uncertainty estimates, especially when uncertainties are small. Lognormal distribution is a transformation of normal distribution, and frequently gives a good presentation of the physical quantities that cannot have any negative values. [Morgan & Henrion 1990; Li & Frey 2002]. When an expert uncertainty estimate is needed, the selection of probability distribution should be made very carefully. There are different techniques for formal expert elicitation procedures where the formulation of the PDFs is based on interviews of experts [Morgan & Henrion 1990].

When input parameter uncertainties are defined, they have to be combined to obtain the total uncertainty in model output (step 3). Methods to combine uncertainties include fuzzy arithmetic, propagating the absolute error, analytic probabilistic techniques and stochastic simulation.

Maximum error can be calculated by propagating the absolute errors, i.e. using partial differential for each variable with respect to the function to be calculated and consequently by calculating the total differential. This method has been used e.g. by Heijungs [1996] for uncertainty assessment of LCA. If input parameter uncertainties are defined as fuzzy numbers, uncertainties can be combined using fuzzy arithmetic as described by Scherm [2000] and Chevalier & Le Teno [1996].

When uncertainties are described by PDFs, the possible choices for combining uncertainties include analytic methods and stochastic simulation. Analytic methods are accurate, but numerical integration is required in all cases except the simplest. To avoid numerical integration, Taylor series expansion can be

used. First order Taylor series expansion is easy to apply and it can be used if uncertainties are normally distributed, small enough, and functions are smooth. The Tier 1 method of the IPCC [2000a] to combine uncertainties in GHG inventories is based on first order Taylor series expansion. In the cases where the assumptions needed for first order Taylor series expansion do not hold, higher order moment methods can be used. However, these analytical methods get rapidly algebraically complicated if correlations exist or the used models are complex. Another disadvantage of higher order moment methods is that information about output distributions is sparse if other than normal distributions are used. [Morgan & Henrion 1990].

Stochastic simulation (sampling techniques) seems to be the most appropriate method to combine uncertainties when the models are complex, non-linear, or correlations occur [Morgan and Henrion 1990, p. 214]. When calculation capacity of personal computers has increased, the previous problem with stochastic simulation – long time needed for sufficiently large number of model runs – has diminished.

Sampling techniques include Monte Carlo and Latin Hypercube Simulation. In Monte Carlo simulation, either empirical or parametric distributions can be used as inputs. Random numbers are taken from each input distribution many times, and as a result, probability distribution of the output is obtained. LHS is an application of MC, where PDF is divided to sections with equal probabilities. For LHS, calculation capacity needed is smaller than for MC. LHS was used, for example, in the uncertainty assessment of GHG inventory of the UK [Charles et al. 1998].

Monte Carlo simulation is recommended by the IPCC [2000a] as the Tier 2 method for combining uncertainties in GHG inventories. It has also been used for this purpose in various countries, for example in Austria [Winiwarter & Rypdal 2001]. Furthermore, it has also been used in various other environmental studies [Lo et al. 2005; Int Panis et al. 2004; Maurice et al. 2000; Kumar et al. 2004].

1.5 Objective and scope of the thesis

The objective of this thesis is to estimate greenhouse impact caused by a country or a country group due to GHG emissions. Furthermore, the objective of the study is also to give information on the possibilities and methods to increase reliability of the mitigation measures of global warming by reducing uncertainty in estimates of GHG emissions or removals. The study focuses on gases included in the Kyoto Protocol (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6). Due to reporting requirements set in the Protocol, quality and uncertainty of emission estimates of these gases are of special interest.

The greenhouse impact caused by a country is assessed by using two different approaches. Firstly, the impact is estimated dynamically by examining radiative forcing due to both historical and expected future emissions. Secondly, for a shorter time period during which detailed inventories of greenhouse gases are available, impact is estimated by assessing Finland's share of global annual emissions taking uncertainties in the estimates into account. These shares are compared with Finland's share of global population and GDP. The scope of the research is illustrated in Figure 4.

The objective of Article I was to assess the radiative forcing impact caused by anthropogenic GHG emissions (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) from Finland. A new version of the REFUGE model programmed earlier at VTT (Korhonen et al. 1993) was developed, and the model was equipped with new features. The study focuses on comparing different ways of considering RF caused by a country or an activity that causes only a small share of global RF. The study estimates the warming effect caused by Finland from 1900 to 2100 and compares different emission scenarios.

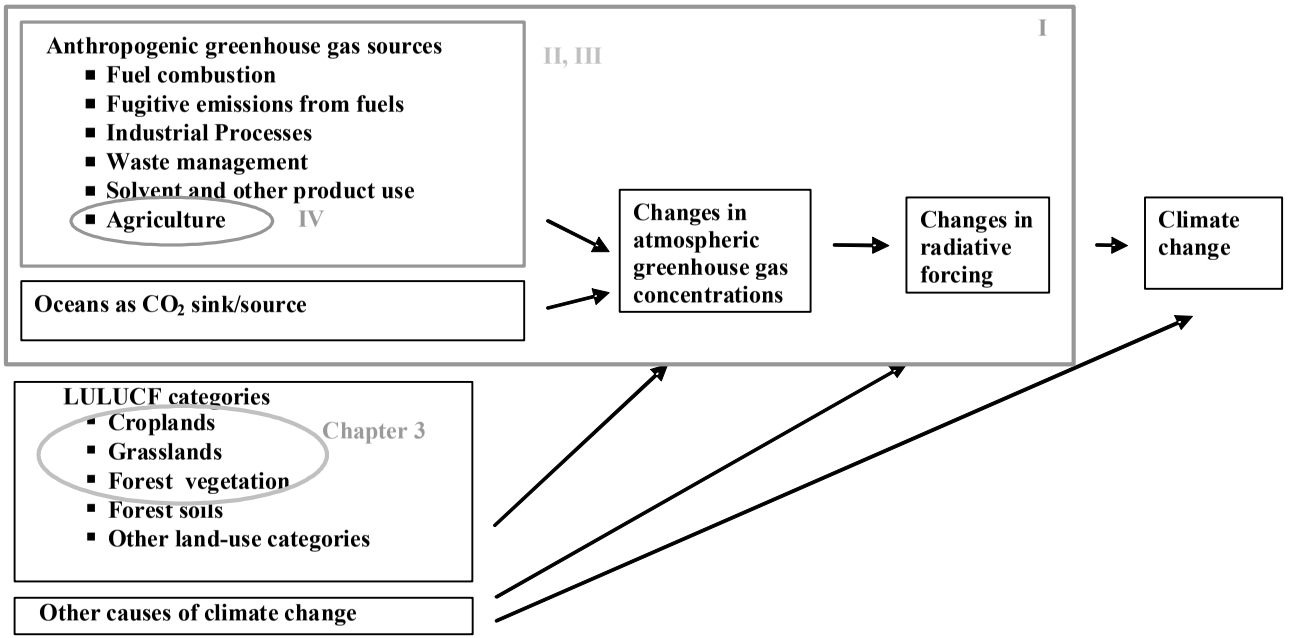

Figure 4. A simple overview of factors that have an effect on climate change. Grey ovals and boxes indicate the coverage of different parts of the thesis. Geographical coverage of the study is Finland in all other articles than III, in which the geographical coverage is the EU.

As a Party to the United Nations Framework Convention on Climate Change (UNFCCC), Finland is obligated to estimate and report greenhouse gas emissions and removals annually, and to incorporate estimates with assessment of uncertainty [FCCC 1999; 2003; 2004]. The annual emissions from Finland are estimated by various organisations, and the annual GHG inventory is compiled by Statistics Finland [Statistics Finland 2005]. To be able to fulfil the requirement of uncertainty estimates, Finland performed the first preliminary uncertainty estimate for the 1998 and 1999 inventories [Pipatti 2001; Aaltonen et al. 2001]. The first uncertainty assessment was done mainly by using expert estimates of the magnitude of uncertainties, and by combining uncertainties using simple error propagation equations. After the completion of the first uncertainty estimate, a need for a more detailed assessment became apparent. A need to estimate uncertainties and their causes in more detail was obvious, as also the need to utilise the advantages of a more advanced uncertainty estimation method (Tier 2) recommended by the Intergovernmental Panel on Climate Change [IPCC 2000a]. This need was a starting point for the development of the KASPER model.

First version of the KASPER model developed in this thesis was reported in Article II. The aim was to assess uncertainties in input data, estimate total inventory uncertainty by using stochastic simulation, and to estimate validity of the method used. The objective was also to present a sensitivity analysis for both identification of the most important source categories and for assessment of effect of certain choices done during the modelling process. The results were also reported in a conference paper [Monni et al. 2003] where the importance of methane and N_2O on total inventory uncertainty was assessed in more detail.

According to the results in Article II, agriculture is an important contributor to uncertainty, including the most uncertain component in many GHG inventories of the Parties to the UNFCCC – N_2O from agricultural soils. Thus, the objective of Article IV was to assess uncertainty in agriculture in more detail in order to find the most relevant measures that could lead to reduction of uncertainty in this category.

Since the 2005 inventory submission, Annex I Parties of the Kyoto Protocol have been liable to quantitatively estimate uncertainties in greenhouse gas emissions and removals from LULUCF in addition to other categories [FCCC

2004b]. Therefore, there was a need to integrate all the features presented in Articles [II; IV; Monni et al. 2003] in the KASPER model, and to extend it to cover all LULUCF categories that Finland reported to the UNFCCC in 2005. Results of the latest version of KASPER model are presented in this thesis (Chapter 3) and also in the National Inventory Report of Finland submitted to the UNFCCC [Statistics Finland 2005]. Finally, the effect of uncertainty on the estimated share of Finland's of global emissions is assessed in this thesis.

The motivation of the uncertainty analyses presented in the thesis was to give reliable estimates of uncertainties involved in greenhouse gas inventories that are comparable across different emission categories under the UNFCCC (energy, transportation, product use, industry, agriculture and waste). Categories related to LULUCF that can act both as sinks or sources of greenhouse gases are considered to a lesser extent. When preparing quantitative uncertainty estimates, possible sources of bias in e.g. data collection, emission factors and emission calculation procedures were also qualitatively assessed.

Due to beginning of EU emissions trading (2005-2007) and the forthcoming Kyoto emissions trading, where GHG emissions gain an economic value, uncertainties in emissions to be traded gained attention. The objective of Article III was to compare uncertainties in different emissions trading schemes. An extended application of KASPER was developed, which extended the geographical coverage from Finland to EU-15 and EU-25. In addition, uncertainties in the CO_2 emissions in sectors covered by the EU ETS were distinguished from uncertainties in sectors not included in the EU ETS, taking into consideration bounds for uncertainty given by the Guidelines for Monitoring [EC 2004].

Coverage of emissions sources in estimation of radiative forcing [I] is nearly the same as in the first version of the KASPER model [II; IV; Monni et al. 2003]. The emission categories included are CO_2 from fuel combustion, industrial processes and fugitive emissions from oil and natural gas. CH_4 emission categories include fuel combustion, fugitive emissions from oil and natural gas, industrial processes, agriculture and waste. In the KASPER model, fugitive CO_2 and CH_4 emissions from peat production were included, but historical emissions were not available and could therefore not be included in the REFUGE2 model for historical years. N_2O estimates include fuel combustion, industrial processes,

product use, agriculture and waste. For HFCs, PFCs and SF_6, all known sources (industrial processes) are included in the models. The same categories are included in the extended version of KASPER model for the examination of uncertainties at the EU level [III], extended with rice cultivation and some industrial processes not occurring in Finland. In addition, tentative estimates of sink to be credited in accordance with Articles 3.3 and 3.4 of the Kyoto Protocol are included in the model at EU level [III].

The latest version of the KASPER model (presented in Chapter 3 in this thesis), includes all the categories Finland reported to the UNFCCC in 2005, including a number of LULUCF categories. At the same time, the category 'Fugitive emissions from arable peatlands' reported in the Energy sector was removed from the model, because it was no longer reported in the National Inventory Report [Statistics Finland 2005].

When uncertainties in GWP-weighted emissions were estimated, uncertainty in GWP values was not included in the estimates due to decisions taken on the use of constant GWP values in GHG inventories [FCCC 1999].

2. Methods

2.1 Emission estimates

Articles II and IV estimated uncertainties involved in emission estimates of the National GHG Inventory in Finland. Respective emission estimation methods are described in the National Inventory Report that Finland submitted to the UNFCCC [Statistics Finland 2005]. Estimation of emissions in energy, transportation and industry sectors are mainly based on multiplication of activity rate with the corresponding emission factor. Emission factors are based on measurements, literature, theoretical arguments and expert judgements, and also on IPCC recommendations [IPCC 2000a; IPCC 1997a]. For the purposes of the KASPER model developed in this thesis, energy sector was treated at a more aggregated level than in the original calculations. In agriculture and waste sectors, more complex models are used for emission estimation. For example, CH_4 emissions from landfills are estimated using a dynamic model that describes degradation of different waste components using exponential functions. In agriculture and waste sectors, emission calculation models were integrated in the KASPER model as such.

In the LULUCF sector (presented in Chapter 3 in this thesis), emissions in organic grasslands and croplands, biomass burning, fertilisation and lime application are calculated by using emission factors and activity data values, and the same calculation was implemented in the KASPER model. In categories describing carbon stock change in forest biomass and carbon stock change in mineral grasslands and croplands, calculation of emissions or removals is more complex, as described in the NIR [Statistics Finland 2005]. In these categories, a calculation of uncertainties in the KASPER model was made at an aggregated level, because estimates of uncertainties at the level of calculation were not available.

In Article III, uncertainties in different emissions trading schemes were compared. In this Article, emission estimates used in the calculation were based on the EC Inventory Report [Gugele et al. 2004] and on the Inventory Reports presented by the new EU member states for the year 2002 [UNFCCC 2004]. Also, accepted national allocation plans for CO_2 emission allowances for the period 2005–2007 [EEA 2005] were used. In the study, assumption on

proportion of process and combustion related emissions was required, as well as estimates on the assumed amounts of emissions included in the inventory that will be subject to emissions trading.

In Article I, radiative forcing due to greenhouse gas emissions from Finland was assessed. Historical and future GHG emission estimates were based on literature [Lehtilä and Tuhkanen 1999; Sarkkinen et al. 2001; Kara et al. 2001] and on extrapolation for future emissions where needed. Emission scenarios of the IPCC [IPCC 2000b] were used to estimate corresponding background concentrations in the atmosphere (p. 405 in [I]).

2.2 Modelling radiative forcing

For the modelling of radiative forcing, pulse response model (REFUGE2) was developed, based mainly on the Third Assessment Report of the IPCC [2001a] and on the previous model developed at VTT [Korhonen et al. 1993].

Atmospheric concentration of GHGs due to emissions was calculated as an integral (Eq. 1) [Maier-Reimer & Hasselmann 1987]:

$$c(t) = \int_{t_0}^{t} E(u) f(t-u) du + c_0 \qquad (1)$$

where *E(u)* denotes emissions in year *u*, *f* is the pulse response function of the GHG and c_0 denotes undisturbed concentration of the GHG.

Circulation of carbon was modelled by using pulse response functions that represent carbon fluxes between oceans and the atmosphere (Eq. 2) [Maier-Reimer & Hasselmann 1987]:

$$f_{CO2}(t) = a_0 + a_1 e^{-t/\tau_1} + a_2 e^{-t/\tau_2} + a_3 e^{-t/\tau_3} + a_4 e^{-t/\tau_4} \qquad (2)$$

In the REFUGE2 model, three different sets of parameters for the pulse response function were used depending on the step-function increase of CO_2 concentration (Table 2). Different pulse response functions were weighted according to the global background concentration.

Table 2. Parameters of pulse-response function (Eq. 2) used in the REFUGE2 model. Parameters are defined for step-function increases for the initial CO_2 concentration in the atmosphere by factors of 1.25, 2 and 4 [Maier-Reimer & Hasselmann 1987].

Step function	**1.25**	**2**	**4**
$\mathbf{a_0}$	0.131	0.142	0.166
$\mathbf{a_1}$	0.201	0.241	0.356
$\mathbf{a_2}$	0.321	0.323	0.285
$\mathbf{a_3}$	0.249	0.206	0.130
$\mathbf{a_4}$	0.098	0.088	0.063
$\boldsymbol{\tau_1}$ **[yrs]**	362.9	313.8	326.3
$\boldsymbol{\tau_2}$ **[yrs]**	73.6	79.8	91.3
$\boldsymbol{\tau_3}$ **[yrs]**	17.3	18.8	18.9
$\boldsymbol{\tau_4}$ **[yrs]**	1.9	1.7	1.2

Carbon fluxes between atmosphere and terrestrial biosphere are also an important contributor to the natural carbon cycle. In the REFUGE2 model, carbon sources and sinks of the biosphere were considered as external input terms to the model, and therefore, these fluxes were not expressed explicitly in the model. Modelling approach used in the REFUGE2 model presents carbon cycle in rather broad terms, but it fits well with results from other models that describe the carbon cycle more comprehensively. Therefore, the use of REFUGE2 to obtain estimates for the purposes of climate policy in Finland is justifiable.

Removal of other Kyoto gases except CO_2 (CH_4, N_2O, HFCs, PFCs and SF_6) from the atmosphere is more straightforward, and the accuracy of the model is better with them. The removal of these gases from the atmosphere can be modelled using one exponential function only (Eq. 3) [IPCC 1997b]:

$$f(t) = e^{-t/\tau} \tag{3}$$

where τ denotes the lifetime of the GHG in the atmosphere.

Of these gases, only the fluorinated gases have constant lifetimes. In the case of N_2O and CH_4, the atmospheric concentration of these gases has an effect on their lifetimes, which was also taken into account in the model (Table A2 in [I]).

All GHGs absorb radiation in a particular range of wavelengths. Therefore, saturation occurs, when greenhouse gas concentrations in the atmosphere increase at a high enough level. Radiative forcing due to increase in atmospheric concentration of CO_2 was calculated according to Eq. 4 [IPCC 2001a]:

$$\Delta F_{CO2} = 5.35 \ln\left(\frac{C}{C_0}\right) \tag{4}$$

where C denotes CO_2 concentration in the atmosphere and C_0 denotes undisturbed concentration.

Overlap of the range of wavelengths for CH_4 and N_2O was taken into account in the REFUGE2 model. Radiative forcing due to increase in CH_4 and N_2O concentration was estimated by Eq. 5 and 6, respectively [IPCC 2001a]:

$$\Delta F_{CH4} = 0.036(\sqrt{M} - \sqrt{M_0}) - \left[g(M, N_0) - g(M_0, N_0)\right] \tag{5}$$

$$\Delta F_{N2O} = 0.12(\sqrt{N} - \sqrt{N_0}) - \left[g(M_0, N) - g(M_0, N_0)\right] \tag{6}$$

where M denotes CH_4 and N N_2O concentration in the atmosphere. M_0 and N_0 are undisturbed CH_4 and N_2O concentrations, respectively. The equation for g(M,N) is presented in Article I (Equation A7).

Saturation is not important for the fluorinated gases because their atmospheric concentrations are very low. Therefore, Eq. 7 was used to calculate radiative forcing of F-gases [IPCC 2001a]:

$$\Delta F_{F-gas} = A_{F-gas}(X - X_0) \tag{7}$$

where A is a gas-specific constant for radiative forcing of an F-gas, X denotes atmospheric concentration of the F-gas and X_0 undisturbed concentration of the F-gas.

The REFUGE2 model contains two different approaches for the estimation of radiative forcing. In the first one (average forcing, Eq. 8), radiative forcing caused by a country or an activity is proportional to the additional GHG concentration caused by the country or the activity when compared with global radiative forcing and global concentration, respectively.

$$\Delta F_{ACT} = \Delta F_{GLOB} \frac{\Delta c_{ACT}}{c_{GLOB} - c_0} \tag{8}$$

where ΔF_{GLOB} denotes global change in radiative forcing and ΔF_{ACT} denotes change in radiative forcing due to the activity in question. Δc_{ACT} denotes concentration change in the atmosphere due to the activity. c_{GLOB} denotes global atmospheric concentration and c_0 undisturbed concentration.

In the second approach (marginal forcing, Eq. 1 in [I]), the saturation effect occurring in the atmosphere is taken into account in the modelling. It suits the estimation of RF caused by relatively small contributors, but marginal forcings (calculated by the REFUGE2 model) cannot be summed up on a global level, because in this case total forcing would be underestimated. In the marginal forcing approach, a country or activity gets 'benefits' from the saturation already occurred in the atmosphere.

2.3 Estimating input parameter uncertainties

A 100(1–α)% confidence interval for a parameter θ can be expressed according to Equation 9 [Milton & Arnold 1995]:

$$P\left[L_1 \le \theta \le L_2\right] = 1 - \alpha \tag{9}$$

where L_1 and L_2 are the lower and upper bounds of the confidence interval and α denotes the probability that θ is outside the range defined by L_1 and L_2. α is 0.05 for calculations presented in this thesis.

In GHG inventories, it is common to express uncertainties as lower and upper bounds (U_- and U_+) of the 95% confidence interval expressed as percent relative

to the mean value [IPCC 2000a; IPCC 2003; Rypdal & Winiwarter 2001; Winiwarter & Rypdal 2001] (Eq. 10):

$$U_{-} = \left| \frac{E_t - L_1}{E_t} \right| \times 100\% \qquad (10)$$

$$U_{+} = \left| \frac{L_2 - E_t}{E_t} \right| \times 100\%$$

where E_t denotes the mean value of emissions or removals in year t.

When uncertainty distribution is symmetrical, uncertainty is often described as ±U (e.g. ±10%). If uncertainties are asymmetrical, they are described as ranging from $-U_{-}$ to $+U_{+}$ (e.g. -70 to +150%). When uncertainties are defined by using two-parametric distributions (e.g. normal or lognormal distributions), they are perfectly defined by using the expression given in Eq. 10. If distributions have three or more parameters, Eq. 10 does not give sufficiently detailed information for the construction of the distribution unambiguously.

Correlation between two input variables can be expressed by Pearson correlation coefficient [Milton & Arnold 1995, p. 425] (Eq. 11):

$$\rho = \frac{COV(X,Y)}{\sqrt{VAR(X)VAR(Y)}} \qquad (11)$$

where *COV(X,Y)* denotes covariance of parameters *X* and *Y* and *VAR(X)* and *VAR(Y)* denote variances of *X* and *Y,* respectively.

Pearson correlation coefficient assumes values between [-1, +1], where ±1 presents a perfect positive or negative correlation, whereas 0 indicates no linear relationship between the variables [Milton & Arnold 1995]. When two distributions have a non-linear but monotonic dependence, rank-order correlation can be used [Li & Frey 2002; Morgan & Henrion 1990]. In rank-order correlation, a set of simulated values are arranged in ascending order before calculating the model output. Then, arranged values are used, i.e. for correlated assumptions first, the lowest, then the second lowest values are taken,

etc. This method was used to correlate variables when it was impossible to model them explicitly in the KASPER model.

In the input parameter uncertainty estimates in this thesis, the possible sources of uncertainty presented in Section 1.4 were examined. Input parameter uncertainties were estimated using domestic and international literature, available measurement data, IPCC default uncertainties and expert judgements (Table 1 in [II]).

In the energy sector, differences between import and export statistics and fuel consumption estimates based on a bottom-up approach gave an indication of bias for imported fuels (coal, oil, natural gas). For domestic fuels (peat and biofuels), uncertainties in activity data were larger, due to variability in fuel quality and the use of untraded fuels (e.g. use of product residues in pulp and paper industry). CO_2 emission factors for combustion were rather accurately known, because carbon content of the fuels is nearly constant, and nearly all carbon in the fuel is oxidised. Even for peat, emission factors do not vary notably between different types of peat [Vesterinen 2003].

The derivation of uncertainties of CH_4 and N_2O from combustion was more complex. For example, the real annual average emission factor for N_2O for each power plant depends on fuel, plant operation and maintenance, plant size and age, combustion technology etc. The CH_4 and N_2O emissions from each power plant may have large variation depending on operating conditions. In the GHG inventory of Finland, there is an extensive calculation system that defines the emission factor for each power plant by taking into account plant size, technology and main fuel. However, even within each category, there is variation between plants, and between the real average annual emission factors. In the uncertainty assessment, it was not possible to make detailed estimates on that calculation level. Firstly, it would have been very time-consuming to include all thousands of plants to the KASPER model. Secondly, there would have been many cross-correlations between categories, because emission factors are largely derived using data from the same sources, and because the same emission factor is often used for many categories. In addition, possible bias in emission factors would very likely be correlated across different plants. Estimation of such cross-correlations would have been crucial, since ignorance of correlations could have lead to significant underestimation of uncertainties.

Therefore, uncertainty calculation was done at a more aggregated level, taking the main category of emissions at third CRF level (e.g. 1.A 1. Public Electricity and Heat Production) and type of the fuel (e.g. solid, liquid) when estimating uncertainties in emissions of non-CO_2 gases.

In the agriculture sector, uncertainties in input parameters were estimated in detail, based on literature, measurements, data collection methods etc (see Tables 1–5 in [IV]). Uncertainties were applied directly to the calculation model.

For CH_4 emission estimates from landfills, a rather complex dynamic model (FOD model) is used, and therefore also a possible bias in the model structure has to be taken into account in uncertainty analysis. There are several ways for assessing model uncertainty. In this thesis, different approaches to treat model uncertainty were used. In some cases, model uncertainty was included in parameter uncertainty estimates. For example, uncertainty ranges given for waste degradation coefficients were large in order to describe also possible model uncertainty, e.g. possible over-simplification of the phenomenon. In addition, in estimates of carbon stock changes in mineral croplands, uncertainty ranges estimated for emissions/removals were larger than could be obtained by combining parameter uncertainties in the model in order to also describe the possible model uncertainty. However, in general, model uncertainty and other types of bias are difficult to estimate. If calculation errors are found, they are usually corrected before compiling the uncertainty assessment. In some cases, it was suspected that emission factors used in the inventory, based on IPCC defaults, overestimated emissions in Finland. However, because there was not enough data available to compile country-specific emission factors, the IPCC defaults were used. In these cases (e.g. last row in Table 3 in [IV]) uncertainties were modelled with negatively skewed distributions.

Correlations between input parameters were modelled explicitly in the model structure – as far as possible – especially in cases where uncertainty calculation was added to entire models (e.g. in waste and agriculture sectors). On the other hand, when simpler models were used for the estimation of uncertainty than the actual calculation of emissions (e.g. in energy sector), aggregation of sectors was done in a way that enabled avoiding cross-sectoral correlations.

Greenhouse gas inventory and uncertainty estimates are updated annually, and therefore some revisions to the KASPER model have taken place after the publication of Article II. Emission estimation methodology for mineral products and fugitive emissions from oil and gas has been refined, and new uncertainty estimates corresponding to new methods have been compiled at Statistics Finland. The uncertainty assessment of F-gases is also annually updated in the Finnish Environment Institute, and the results for each year were included in the KASPER model. In addition, some minor revisions to the officially reported uncertainty calculation were made for the 2002 inventory. These include N_2O from road transportation, simulation approach for fuel use and methane emissions from wastewater [Monni 2004]. Chapter 3 in this thesis presents results of the latest uncertainty estimate prepared for the 2003 inventory, including a more detailed analysis for agriculture [IV] and the first uncertainty estimate of LULUCF categories reported also in NIR 2005 [Statistics Finland 2005].

In Article III, where uncertainties were discussed at EU level, estimation of uncertainties was somewhat different from the method used for Finland. Typical uncertainties estimated by different member states were used, in addition to accepted uncertainties from the Guidelines for Monitoring for sectors covered by the EU ETS. Uncertainties were estimated for the EU as a whole, not separately for different member states. In addition, studies comparing uncertainties in EU-15 and new EU member states were used [Suutari et al. 2001].

In this thesis, uncertainties are expressed as probability density functions (PDF). The exact shape of uncertainty distribution is seldom accurately known. The choices made for the purpose of this thesis must therefore be considered as 'best estimates' of the shape of distribution. Selection of distribution was based on, e.g. the range of possible values (e.g. non-negative real axis) and assumptions on skewing of distributions (positively or negatively skewed). Activity data uncertainties and relatively small uncertainties in emission factors (typically <60%) were mostly described by using normal distributions. Lognormal distribution was used mostly for asymmetrical emission factor uncertainties. In addition, some other PDFs were used, when neither normal nor lognormal distribution was suitable for describing uncertainty. Examples include gamma distribution used for highly asymmetrical uncertainties and beta distribution for negatively skewed uncertainties. The effect of the shape of the distribution on

model output was examined in sensitivity case C in Article II and sensitivity cases F and G in Article IV.

2.4 Estimating trend uncertainties

Greenhouse gas emissions trend describes the emission changes related to the base year of the inventory according to Eq. 12:

$$Trend_{b,t} = \frac{E_t - E_b}{E_b} \tag{12}$$

where E_t and E_b are GHG emissions in year t and in the base year of the calculation (1990 in Kyoto Protocol for most industrial countries).

It is important to note that the GHG emissions or removals trend describes the change in emissions or removals between two points of time. Therefore, time series between the two points of time is not taken into account.

Trend uncertainty is described with 95% confidence interval as in Eq. 9, but trend uncertainty is often given as percentage points rather than percent relative to the mean value (Eq. 13):

$$\begin{aligned} U_{trend,+} &= L_{2,trend} - Trend_{b,t} \\ U_{trend,-} &= Trend_{b,t} - L_{1,trend} \end{aligned} \tag{13}$$

For example, we can say that trend in emissions is 5%, with an uncertainty of ±3 percentage points. This denotes that for trend, [L_1, L_2] is [2%, 8%]. This expression is used by the IPCC Good Practice Guidance [2000a], and also in the literature related to GHG inventory uncertainties [Rypdal & Winiwarter 2001; Winiwarter & Rypdal 2001].

Trend uncertainty depends on correlation of uncertainties between the two years. Variance in the difference of two random variables is defined as [Morgan and Henrion 1990] (Eq. 14):

$$VAR(E_t - E_b) = VAR(E_t) + VAR(E_b) - 2\rho\sqrt{VAR(E_b)VAR(E_t)} \qquad (14)$$

In this thesis, perfect positive correlation (ρ = 1) was assumed between emission factors in different years. In these cases, the basis for emission factor was the same for both years, and therefore it was assumed that a possible bias (e.g. under over overestimation of the emission factor) in base year would lead to subsequent bias for the inventory year, respectively. For LULUCF categories Carbon stock change in living biomass (forest land), and Carbon stock change in mineral croplands and grasslands the correlation coefficient of 0.8 was used between years. Carbon stock change in soils depends on a longer time period than only one year (20 years time period is used for calculation), and on the other hand, a possible bias in calculation parameters is likely to be common for both years. Therefore, it is obvious that rather strong correlation occurs. The value (0.8) was used as a first approximation. Correlation coefficient could be revised by estimating uncertainties using more detailed models.

2.5 Combining uncertainties

There are various methods to combine input parameter uncertainties to obtain uncertainty in model output, as presented in Section 1.4. For the KASPER model [Articles II–IV], Monte Carlo simulation was selected, because it enables flexible treatment of correlations and possibility to use all kinds of PDFs, and simulation of non-linear models e.g. in waste degradation in landfills. Monte Carlo simulation is also recommended by the IPCC as Tier 2 method for uncertainty estimates of GHG inventories [IPCC 2000a].

Other methods to combine uncertainties presented in Section 1.4 were not considered appropriate for the purposes of this study. Exact analytical methods would have become too complex, and simplifications of analytic methods (e.g. first order Taylor series expansion) would not have been able to handle all the features of the models. Calculation of worst-case scenarios using fuzzy logic as presented e.g. by Scherm [2000] is not of interest for GHG inventories, because their occurrence in the real world is highly unlikely. In the inventory, most input parameters are certainly independent of each other (e.g. activity data for oil consumption, and emission factor for enteric fermentation). Therefore, worst-

case scenarios are not appropriate for the estimation of uncertainty in GHG inventories.

Monte Carlo simulation was carried out by using a commercial software package Crystal Ball [Decisioneering 2000]. The number of simulations needed can be estimated by using the equations presented by Morgan & Henrion [1990, p. 200–203]. For purposes of this study, simulations were continued until a selected precision (i.e. 1% for the E_t and $L_{2,t}$) was achieved. The typical number of simulations was between 30 000 and 50 000. Because input distributions themselves are uncertain, satisfactory results for uncertainty of model output could also be achieved with a smaller number of simulations.

The importance of each parameter for the total uncertainty was also assessed. During simulation, rank-order correlation coefficients were computed between each input parameter and the output of the model (see Fig. 3 in [II] and Fig. 1 in [IV]). In this method, rank values were used instead of the actual sample to calculate correlation coefficients between two variables. The same method has been used, e.g. by Int Panis et al. [2004], Lo et al. [2005] and Li & Frey [2002]. Furthermore, sensitivity of the total results on changes in parameter uncertainties or choices made in the modelling was examined in Articles II and IV.

3. Results

3.1 Radiative forcing

For the calculation of radiative forcing [I], three different scenarios for Finland were used (BAU^C, $KIO1^C$ and $Techno^C$). The corresponding global scenarios used for the calculation of background concentration and radiative forcing were IPCC SRES Scenarios A2, B2 and B1 [IPCC 2000b], respectively. The choice of background scenario was made based on the assumption that socio-economical and technological development are similar in Finland and globally. The GWP-weighted emissions in 1900, 1990 and 2100 used in different scenarios in Finland are presented in Table 3. The GWP values used are those used in the reporting to the UNFCCC [FCCC 1999], but in the calculation of radiative forcing, GWP weighting of emissions was not needed.

Table 3. Emission scenarios for Finland used in the calculations carried out using the REFUGE2 model. GWP-weighted emissions in 1900, 1990 and 2100 are presented by using 100-year GWP values.

Scenario	Emissions in 1900 [Tg CO_2 eq]	Emissions in 1990 [Tg CO_2 eq]	Emissions in 2100 [Tg CO_2 eq]
BAU^C	6	71	128
$KIO1^C$	6	71	68
$Techno^C$	6	71	36

The range of radiative forcing in 2100, calculated using the average forcing approach, varied from 6 to 11 mWm^{-2} which is 2 to 3.5 times more than estimated radiative forcing in 1990 (3.2 mWm^{-2}). The results reveal that in the beginning of 1900's methane (mainly from cattle breeding and waste management) caused the majority of RF from Finland. However, increase in the use of fossil fuels made CO_2 to the main cause of radiative forcing in 1960's. It was estimated that carbon dioxide will remain as the main cause until 2100, because it has a rather long atmospheric lifetime, and because methane has larger reduction potential, which has been taken into account in the scenarios. The share of N_2O of total RF (12%) is not likely to change notably, whereas the share of F-gases is increasing, but remains small until 2100 (Fig. 3 in [I]).

Finland's share of global radiative forcing in 1990 was, according to the calculations (averaged forcing approach), 0.18 %. This is double compared with the share of global population (0.1% in 1990), but only a third of the share of GDP (0.6% in 1990). However, it has to be noted that due to Finland's relatively short emission history, the share of global emissions is higher (0.22%) than the share of radiative forcing. Figure 5 presents Finland's share of radiative forcing in 1900, 1990 and in three scenarios in 2100. The results of all three scenarios in 2100 are close to each other, because the emissions development in corresponding global and Finnish scenarios is similar.

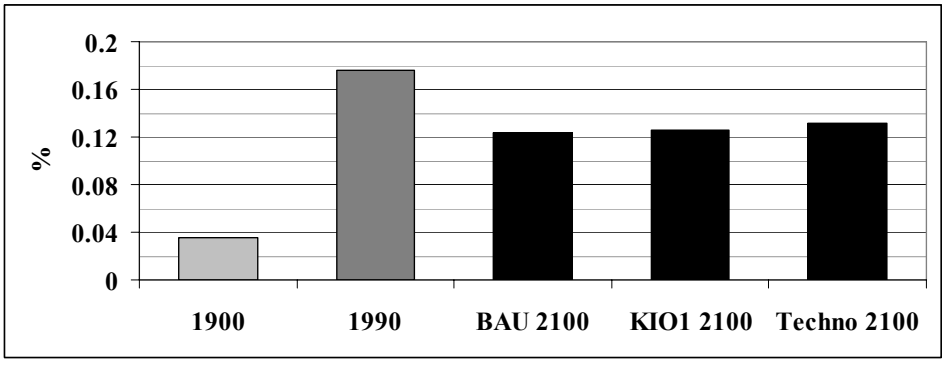

Figure 5. Finland's share of global radiative forcing in 1900, 1990 and 2100 in different scenarios. Radiative forcing was calculated using the average forcing approach. Corresponding global scenarios were A2 for BAU^C, B2 for KIO1^C and B1 for Techno^C.

In all the scenarios considered, radiative forcing increases by 2100 (Fig. 4 in [I]), even in the scenario Techno^C where emissions decrease notably (Fig. 1 in [I]). This is due to inertia in the removal of greenhouse gases from the atmosphere. However, Finland's share of global radiative forcing is decreasing because of more strongly increasing global radiative forcing, especially due to emission increase in developing countries.

The effect of background concentration on radiative forcing caused by CO_2 emissions was from 5 to 9% on results in 2100, when compared with the middle scenario (Fig. 5 in [I]). The effect of the forcing model chosen (marginal or average) had a larger effect, 30–40% (Fig. 6 in [I]).

3.2 GHG emission, removal and trend uncertainties for Finland

According to the uncertainty assessment carried out, uncertainty in anthropogenic GHG emissions from Finland in 2003 was -4 to +8% (upper and lower bounds of 95% confidence interval relative to the mean value), without LULUCF. In 1990 uncertainties were larger, from -6 to +13%. This is mainly due to the magnitude of the most uncertain emission source, N_2O from agricultural soils. The share of these emissions (direct and indirect together) was 6.0% of emissions in 1990, but only 3.7% in 2003. A sensitivity study carried out in this thesis revealed that uncertainties would be ±3% in 2003 and -3 to +4% in 1990, if uncertainties in N_2O from agricultural soils were set to zero. When the categories of land use, land use change and forestry (LULUCF) were included, the uncertainties in net emissions were -14 to +15% in 2003 and -21 to +25% in 1990, respectively. Resulting sectoral uncertainties in 2003 are presented in Figure 6 as CO_2 eq and those by gas in Table 4.

Table 4. GHG emissions and removals from Finland by gas presented as the mean value [Statistics Finland 2005], 95% confidence interval, and bounds of 95% confidence interval as percent relative to the mean value.

Gas	**Emissions/removals [Tg CO_2 eq]**	**95% confidence interval [Tg CO_2 eq]**	**95% confidence interval [%]**
CO_2	55.4	47.0 to 63.7	±15%
CO_2 without LULUCF	73.2	71.7 to 74.9	±2%
CH_4	5.0	3.8 to 6.2	±20%
N_2O	6.7	3.8 to 13.3	-40 to 100%
HFCs, PFCs and SF_6	0.7	0.6 to 0.9	-10 to 20%
Total	67.7	58.5 to 78.1	-14 to 15%
Total without LULUCF	85.5	81.9 to 92.4	-4 to +8%

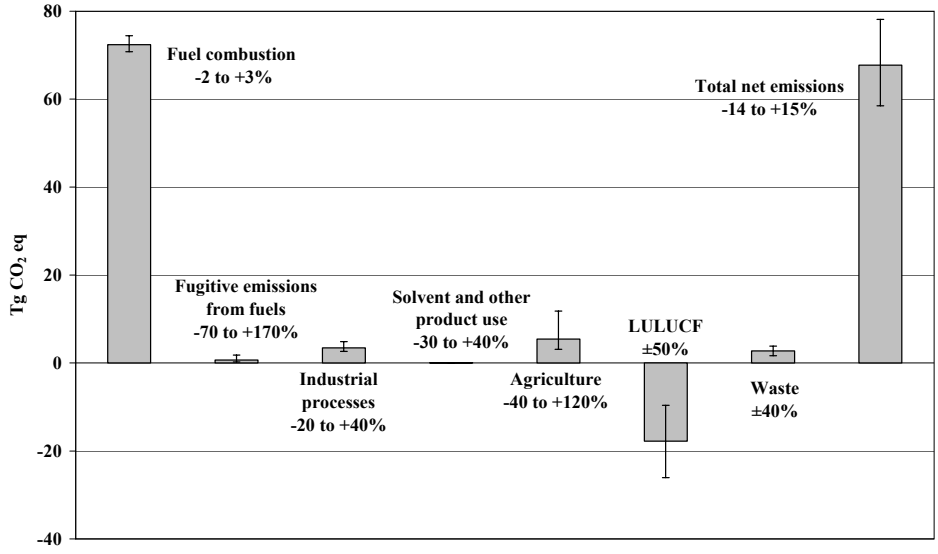

Figure 6. Greenhouse gas emissions and removals from Finland in 2003. Error bars indicate 95% confidence interval. Bounds of confidence interval relative to the mean value are presented in percent for each category.

Uncertainty in total emissions without LULUCF was rather small. That is because majority of emissions comes from sources that are relatively accurately known: 70% of emissions (in 2003) came from sources where upper bound of uncertainty (97.5% fractile relative to the mean value) is <5% and for 84% of emissions uncertainty is <7%.

Carbon dioxide emissions are more accurately known than those of other gases. But when LULUCF categories are included to CO_2 estimates, uncertainties are of the same magnitude as for CH_4, HFCs, PFCs and SF_6. N_2O remains as the most uncertain gas even when LULUCF categories are included in the estimates. The most important contributors to the uncertainty (including all the sectors) in 2003 are presented in Figure 7, and without LULUCF in Figure 8.

Changes in results when compared with Tables 2 and 3 in Article II are mainly due to new categories included in the inventory in the LULUCF sector and industrial processes, and to exclusion of emissions from arable peatlands from energy sector. In agriculture, changes are due to the improved uncertainty

estimate presented in Article IV. For the 2005 inventory submission [Statistics Finland 2005], larger uncertainty ranges were used for N_2O from agricultural soils than in Article II, based on measurement data that showed both large variability between different soils and a possibility of bias in emission factor used for mineral soils [IV]. This change resulted in notable increase in uncertainty estimate of total N_2O emissions and the total emissions from agriculture.

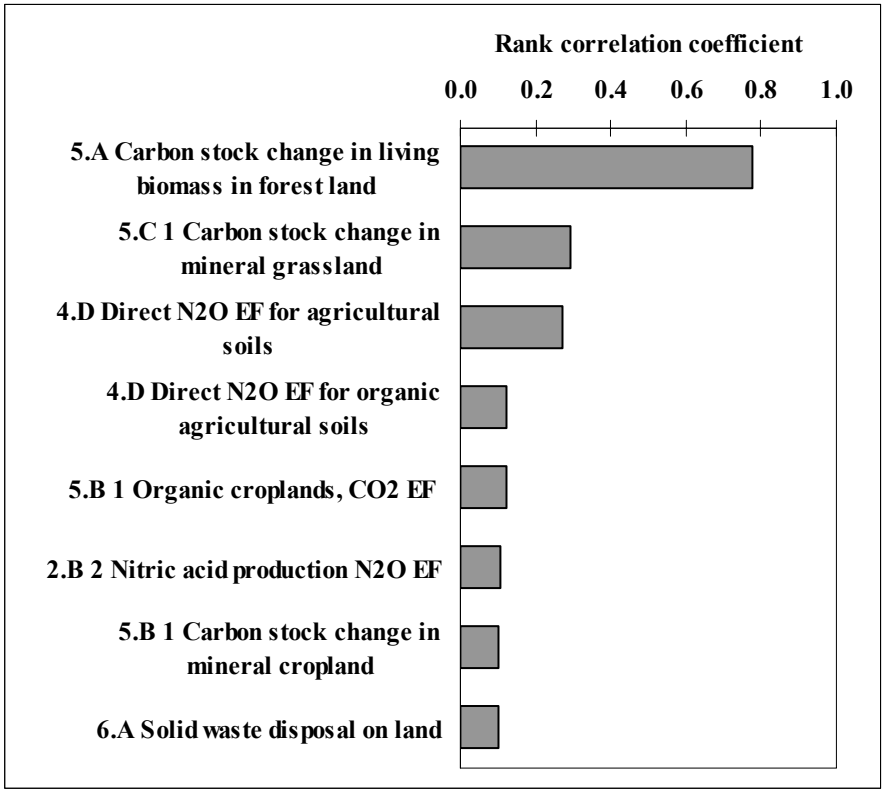

Figure 7. Rank correlation of different input parameters of the KASPER model with regard to the model output (uncertainty in total emissions in 2003).

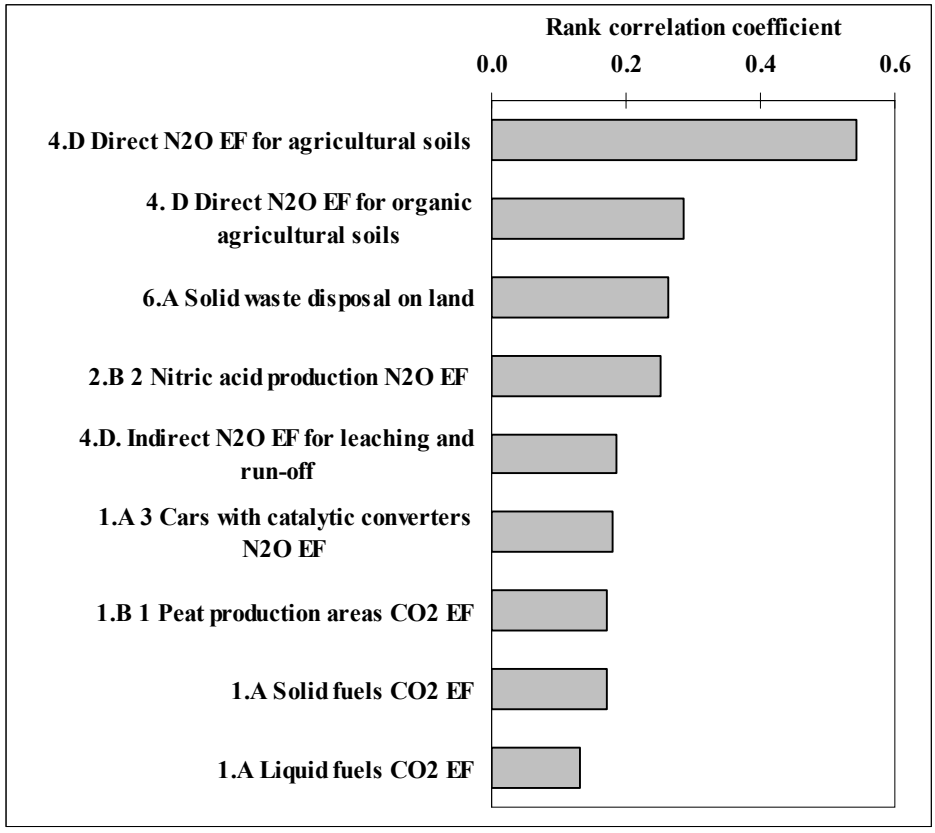

Figure 8. Rank correlation of different input parameters of the KASPER model with regard to the model output (uncertainty in total emissions in 2003 without LULUCF sector).

The most important contributors to the uncertainty were LULUCF categories Carbon stock change in living biomass in forest land, and Carbon stock change in mineral grassland (Figure 7), but it has to be noted that uncertainty estimates of these categories were done rather roughly. When LULUCF categories were not taken into account, the most important categories were N_2O emissions from agricultural soils, CH_4 from solid waste disposal and N_2O emissions from nitric acid production. In Fig. 3 in Article II, activity data in liquid fuel use in small-scale combustion (1.A 4) and other sectors (1.A 5) were also identified as important contributors to the uncertainty. In subsequent versions of the KASPER model, estimation of uncertainty in fuel use was modified. In the new method, information on uncertainty in total consumption was utilised, which set an upper

bound to the uncertainty in different sectors. Based on the more detailed modelling approach, it was concluded that in the first version of KASPER used in Article II, uncertainty in liquid fuel use in sectors 1.A 4 and 1.A 5 was overestimated.

In the Kyoto Protocol, emissions are considered in relation to emissions in the base year. Therefore, uncertainty in the trend of emissions (change between the base year and the inventory year) is also of importance. In 2003, trend uncertainty in Finland was from -6 to +4 percentage points without LULUCF. Negative skewness of uncertainty can mainly be explained by decreasing emissions of N_2O from agricultural soils. When uncertainty in N_2O from agricultural soils was set to zero in a sensitivity analysis, trend uncertainty decreased to ±3 percentage points. Trend is usually expressed as percent relative to the base year, and trend uncertainty as percentage points. In Table 5, trend uncertainties from different countries are compared by using the expressions given in Section 2.4.

Table 5. Trend uncertainty – Finland compared with Austria, Norway and UK.

	Finland	**Austria**[1]	**Norway**[2]	**UK**[3]
$\mathbf{E_b}$ [Tg CO_2 eq]	70.4	79.27	52.0	E_b
$\mathbf{E_t}$ [Tg CO_2 eq]	85.5	82.91	63.0	$0.94E_b$
$\mathbf{E_t}$-$\mathbf{E_b}$ [Tg CO_2 eq]	15.2	3.64	11.0	$0.06E_b$
Trend [%]	22	4.6	21	-6
95% conf interval of trend [%]	+16 to +26	-1 to +10	+17 to +25	-10 to -2
$\mathbf{U_{trend}}$ [percentage points]	-6 to +4	±5	±4	±4

[1]Winiwarter & Rypdal 2001, pp. 5433–5434
[2]Rypdal & Zhang 2000, pp. 11 and 21
[3]Charles et al. 1998

Figure 9 presents time series of net emissions from 1990 to 2003 with corresponding uncertainty ranges for 1990 and 2003 for Finland. The Figure presents net emissions as reported to the UNFCCC, and therefore the figures do not correspond with emissions under the Kyoto Protocol (according to the Kyoto Protocol, only removals from activities under Articles 3.3. and 3.4 can be credited). In the figure, the solid grey line represents trend, i.e. change in mean emissions between 1990 and 2003 (42% increase). Uncertainties between emission estimates in the base year and the end year are strongly correlated. In the modelling, emission factors were assumed fully correlated between the two

years. According to the results, 95% confidence interval of the trend was between 25 and 65%.

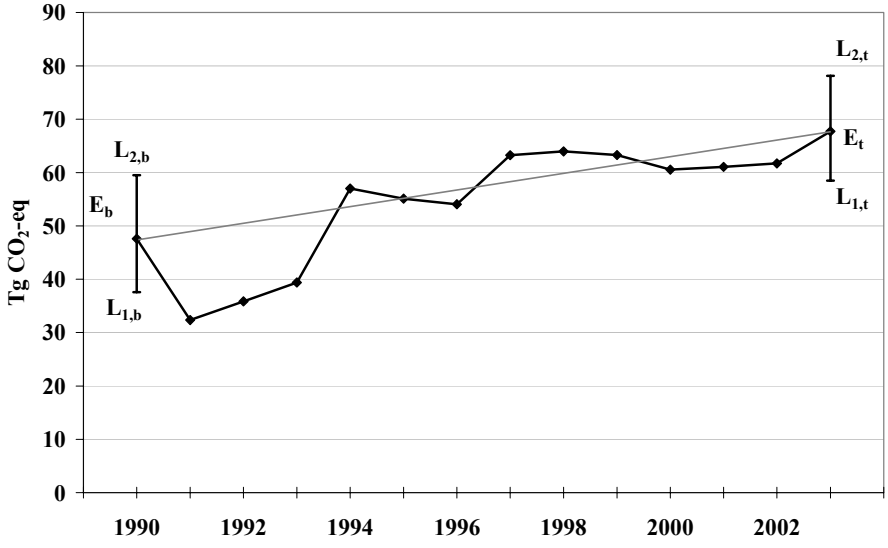

Figure 9. Time series of Finland's net GHG emissions from 1990 to 2003 including all the categories Finland reported to the UNFCCC in 2005 [Statistics Finland 2005]. Error bars present 95% confidence interval for net emissions in 1990 and 2003. Solid grey line presents trend in emissions which is defined as change between 1990 and 2003.

In a sensitivity study [II, case B], the trend uncertainty without LULUCF increased from ±5 percentage points to ±9 percentage points when the correlations across years were set to zero, which also reveals the strong effect of correlations on the results.

In the sensitivity study of total inventory without LULUCF [II], change in input distributions did not have notable effect on inventory uncertainty. But, in the agriculture sector, where asymmetrical uncertainties are more important, effects were notable, resulting in an increase of 60% in L_2 at its highest [IV].

Finland's share of global emissions was assessed roughly, taking uncertainties in emission estimates into account. Estimates and uncertainty ranges used for

global emissions were based on the annual emission estimates given by the IPCC [2001a, 1996] for late 90's or year 2000 (Table 6). Estimates for Finland are those presented in this thesis for 2003.

Table 6. Global and Finnish GHG emissions (without LULUCF). Global emissions are for late 90's or year 2000 and figures for Finland are for 2003. Estimated 95% confidence intervals of emissions are in brackets.

GHG	Global emissions [Tg CO_2 eq]	Finnish emissions [Tg CO_2 eq]
CO_2 (without LULUCF)	23100 (20170 to 26030)	73.2 (71.7 to 74.9)
CH_4	7290 (5470 to 9110)	5.0 (3.8 to 6.2)
N_2O	3360 (1020 to 10080)	6.7 (3.8 to 13.3)
F-gases	360	0.7 (0.6 to 0.9)

To calculate uncertainty in the share of Finnish emissions, the uncertainties in emissions presented in Table 6 were estimated as normally distributed in case of CO_2 and CH_4 and lognormally distributed in case of N_2O. Lognormal distribution was constructed based on the mean value and upper bound of the confidence interval. The share of F-gases of global and Finnish emissions was <1%, and therefore, it was excluded from the analysis. Correlation between Finnish and global emissions is important when estimating the shares. Evidently, some correlation occurs, but its magnitude is difficult to estimate. Therefore, calculations were made for two cases: 1) no correlation was assumed and 2) full correlation was assumed between global and Finnish emissions by gas. Results are presented in Table 7.

According to Table 7, Finland's share of global emissions was 0.2–0.3% in 2003. In the same year, Finland's share of global population was 0.1% [UN Population Division 2003] and share of global GDP 0.4% [UN Statistics Division 2005].

Table 7. Finland's share of global emissions by gas. The two cases represent assumptions of no correlation and full correlation between gas-specific estimates for Finland and globally. Lower and upper bounds refer to the 95% confidence interval.

Gas	Mean value [%]	No correlation		Full correlation	
		Lower bound [%]	Upper bound [%]	Lower bound [%]	Upper bound [%]
CO_2	0.32	0.28	0.36	0.28	0.36
CH_4	0.07	0.05	0.10	0.07	0.07
N_2O	0.20	0.05	1.06	0.13	0.41
Total	0.25	0.21	0.30	0.22	0.28

3.3 Uncertainties in different emissions trading schemes of the EU

In the estimation of uncertainties in different emissions trading schemes of the EU, the emissions were estimated using the National Inventory Reports of the EU-15 and the new member states [Gugele et al. 2004; UNFCCC 2004]. The estimated volume of EU ETS was based on accepted National Allocation Plans [EEA 2005]. The emission estimates and their uncertainties were given by source category and gas. The emissions and corresponding uncertainty estimates for different emissions trading schemes are given in Table 8.

Uncertainties in different emissions trading schemes of the EU (based on uncertainties in inventories) varied from ±3% to over 20% (Figure 10; Table 2 in [III]). Inclusion of the 'new' EU member states to the EU CO_2 ETS did not increase uncertainty notably when compared with uncertainty in EU-15 member states. If CH_4 and N_2O in addition to CO_2 were included in the EU emissions trading scheme (sectors would be kept the same), the market volume of emissions trading would not increase much, but the uncertainties would increase notably. However, this example was a merely hypothetical illustration of the effect of inclusion of these gases into the trading scheme.

Table 8. Emission estimates and their uncertainties used in Article III for comparison of uncertainties in different emissions trading schemes of the EU.

IPCC category[1]	Emission source	Gas	Annual Emissions [Tg CO_2 eq]	Uncertainty [2]
Sources included in EU ETS (EU-15)				
1A	Stationary combustion included in EU emissions trading	CO_2	1370	±3%
2A	Production of cement and lime	CO_2	110	±7%
2C	Metal industry	CO_2	20	±6%
Sources included in EU ETS (New EU member states)				
1A	Stationary combustion included in EU emissions trading	CO_2	480	±7%
2A	Production of cement and lime	CO_2	20	±10%
2C	Metal industry	CO_2	4	±8%
Sources included in extended EU emissions trading scheme in addition to EU ETS (EU-15)				
1A	Stationary combustion (including the same sources as above)	CH_4	6	±50%
1A	Stationary combustion (including the same sources as above)	N_2O	19	-100 to +550%
Sources included in Kyoto emissions trading scheme, in addition to extended EU emissions trading scheme (EU-15)				
1A	Stationary combustion not included above	CO_2	930	±7%
1A	Stationary combustion not included above	CH_4	4	±50%
1A	Stationary combustion not included above	N_2O	10	-100 to +550%
1A3	Transportation	CO_2	840	±5%
1A3	Transportation	CH_4	3	±50%
1A3	Transportation	N_2O	30	-100 to +550%
1B	Fugitive emissions from fuels	CO_2, CH_4	70	±30%
2B	Chemical products	CO_2	10	±20%
2B	Chemical products (e.g. adipic acid and nitric acid production)	N_2O	40	±15%
2	HFC emissions	HFCs	50	±40%
2	PFC emissions	PFCs	5	±40%
2	SF_6 emissions	SF_6	9	±30%
3	Solvent and other product use	CO_2, N_2O	8	±30%
4A	Enteric fermentation	CH_4	140	±40%
4B	Manure management	CH_4	70	±40%
4B	Manure management	N_2O	20	-70 to +150%
4C	Rice cultivation	CH_4	2	-80 to +200%
4D	Agricultural soils	N_2O	190	-100 to +1000%
6A	Solid waste disposal on land	CH_4	80	±45%
6B	Wastewater management	CH_4	70	±50
6B	Wastewater management	N_2O	7	-70 to +150%

6C	Waste incineration	CO_2	9	±20%
5	LULUCF activities under Articles 3.3 and 3.4 of the Kyoto Protocol	CO_2	-30	±90%

[1]Definitions of the categories are not exactly in accordance with IPCC definitions due to division between categories included in and excluded from EU ETS

[2]Lower and upper bounds of 95% confidence interval expressed as percent relative to the mean value. Symmetrical uncertainties were assumed as normally distributed and asymmetrical ones as lognormally distributed except N_2O from agricultural soils, which was assumed as gamma distributed due to high asymmetry.

Inclusion of other sectors (agriculture, waste, transportation, small-scale combustion) would further increase uncertainty. However, inclusion of removals credited under Articles 3.3 and 3.4 of the Kyoto Protocol would only have a minor effect because these removals are estimated small during the first commitment period.

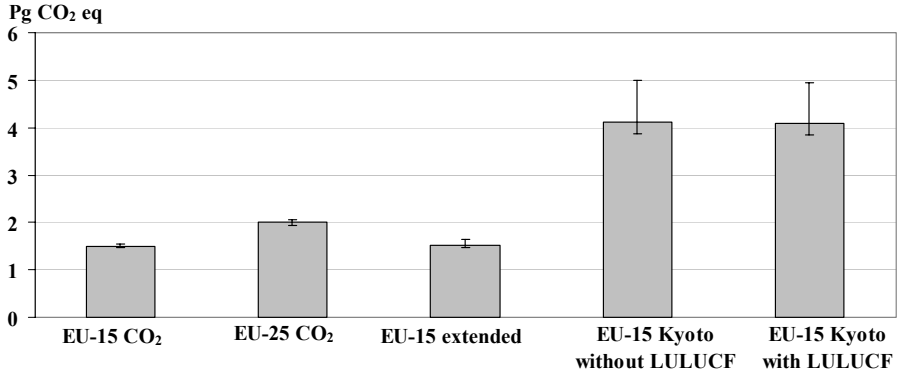

Figure 10. The amount of tradable emissions and their uncertainties in different emissions trading schemes for EU-15 and EU-25. The error bars present upper and lower bounds of 95% confidence interval.

The share of EU-15 of global emissions (CO_2 without LULUCF, CH_4 and N_2O) is around 12% when using the figure presented above for the Kyoto emissions trading scheme and global emissions presented in Table 6. A rough estimate of uncertainty in this share was calculated similarly as in the case of Finland in Section 3.2. The results are presented in Table 9 assuming no correlation between gas-specific global and EU-15 emissions, as well as assuming full correlation between the two estimates. The results with no correlation are likely to overestimate uncertainties.

Table 9. The share of EU-15 of global emissions. The two cases represent assumptions of no correlation and full correlation between gas-specific estimates for EU-15 and globally. Lower and upper bounds refer to the 95% confidence interval.

Gas	Mean value [%]	No correlation		Full correlation	
		Lower bound [%]	Upper bound [%]	Lower bound [%]	Upper bound [%]
CO_2	15	13	17	13	17
CH_4	4	3	6	4	4
N_2O	10	1	71	7	12
Total	12	10	15	11	13

4. Discussion

4.1 Possibilities to reduce uncertainty

During the uncertainty assessment carried out, several possibilities to reduce uncertainties were identified and reported in Articles II and IV. Possibilities to reduce uncertainties are discussed in more detail in this Section. Most of the findings were also reported in the National Inventory Report of Finland [Statistics Finland 2005] by the author.

CO_2 emissions from combustion are well known. CO_2 emission factor mainly depends on the carbon content of the fuel rather than on combustion technology. Therefore, possibilities to reduce uncertainty include more detailed fuel analyses of mixed combustion and domestic fuels such as peat and waste.

In the case of gases other than CO_2, uncertainty in the amount of biomass combusted (activity data) is also of importance. Industries burning product residues or households combusting wood are sources where activity data uncertainties can be notable. On the other hand, emission factor uncertainties for CH_4 and N_2O are rather large, and therefore reduction of uncertainty in activity data may not result in notable reduction of total uncertainty in the emission sources.

Uncertainties in some emission sources (typically CH_4 and N_2O from stationary combustion, and CO_2, CH_4 and N_2O from industrial processes) could be reduced with continuous measurement of emissions. These emissions depend on fuel type, boiler design and maintenance and process conditions (e.g. temperature and residence time in furnace, air fraction, NO_x-control techniques). Therefore it is difficult to give representative average emission factors for the gases. Where continuous measurement is too expensive, more representative data could be gathered, and dependencies between available process parameters (e.g. temperature in the furnace, fuel load) and GHG emissions could be formulated. A measurement project with questionnaire survey that aims to find such dependencies is currently on-going at VTT. The aim of the project is to reduce uncertainty in emission factors used. In addition, more detailed uncertainty estimates could be obtained by analysing cross-correlations between emission factors for different technologies and size-classes.

In small-scale combustion of biomass, CH_4 emissions depend much on the fuel and furnace used. There is not much information available on the emissions, and international data cannot be applied directly, because the design of furnaces, fuel used and the means of combustion vary. To be able to decrease uncertainty, more measurement data would be needed from different types of furnaces used in Finland (more information will be gained during 2005 in a project by VTT). In addition, more data on currently used furnaces and small-scale boilers, as well as data on the amount and type of fuels used are necessary for the development of better models.

In transportation, the formulation of representative emission factors and the estimation of frequency of different types of driving conditions (as is done in the LIPASTO [2005] model used in the GHG inventory) are particularly important. This is because continuous measurements cannot be implemented to each vehicle. On the other hand, the number of different vehicles is large, and therefore uncertainty in the annual mean value is substantially smaller than variability between different vehicles, if unbiased emission factors can be formulated.

Emissions from peat production areas are an important contributor to the uncertainty in Finnish GHG inventory (see Figure 8). The on-going measurement project "Greenhouse Impact of the Use of Peat and Peatlands in Finland" will produce more measurement data and generalize the data with help of models to be used in national GHG inventory. When these results will be available, uncertainty of both the emission estimate and the uncertainty estimate is likely to decrease. However, it is likely that even when the results of the measurement campaigns are available, uncertainties will remain rather high, due to difficulties to model different types of peatlands, different weather conditions, etc. Measurements in this category are rather costly, and continuous measurements are not a practical means to estimate emissions.

The possibilities to reduce uncertainty in agriculture sector are discussed in detail in Chapter 4 in Article IV. The sensitivity study revealed that uncertainty in total agricultural inventory would be 7% points lower if more accurate methods were used, including 1) improved data collection in organic soils area estimates, 2) more detailed CH_4 estimation methods for enteric fermentation, and 3) climate-specific methods for N_2O from agricultural soils (Table 8 in [IV]).

Regarding the 3rd point in the list, Article IV discussed the fact that measurement campaigns conducted in Finland did not give data that would be representative enough to be used in the national inventory. Therefore, it was concluded that gathering data from Finland alone would be too expensive, and a better solution would be to formulate climate-specific methods utilising data from different countries, as already presented in literature [Freibauer 2003].

In the waste sector, solid waste disposal on land is the most important contributor to the uncertainty. Waste degradation in landfills is a rather complex process. To decrease uncertainty, models could be verified by using representative measurement data from landfills with different conditions. In addition, more data on the composition of waste could be collected. However, waste degradation model uses input data from the beginning of 1900, and the quality of data from the historical years is difficult to enhance retroactively.

For LULUCF sector, uncertainties are rather large. It is evident that in most of the categories, reduction of uncertainty is difficult, due to complex processes and varying conditions across the country. Reduction of these uncertainties is also costly. On the other hand, under the Kyoto Protocol, the amount of sink to be credited is limited. Due to the cap set on sink credits, effect of LULUCF category on total inventory uncertainty will be smaller for reporting under the Kyoto Protocol than in inventories under the UNFCCC. In the case of EU [III], inclusion of activities under Articles 3.3 and 3.4 of the Protocol did not increase total uncertainty notably when compared with inventory without LULUCF.

4.2 Evaluation of the results

4.2.1 Radiative forcing

The REFUGE2 model developed in this thesis is a rather simple model that describes increase in atmospheric GHG concentrations and radiative forcing due to anthropogenic emissions of CO_2, CH_4, N_2O, HFCs, PFCs and SF_6. Uncertainty in radiative forcing calculations was not assessed quantitatively. However, radiative forcing calculation contains uncertainties due to uncertainties in historical, current and future emissions, calculation of atmospheric GHG concentrations and finally, uncertainties in estimating radiative forcing due to particular atmospheric

concentration. GHG emissions from Finland in 2003 contained an uncertainty of around -4 to +8% when LULUCF sector was not included. Uncertainty in historical emissions is larger, but the effect of historical emissions decreases when calculation period increases. Methane has a rather short atmospheric lifetime (around 7–11 years depending on atmospheric concentration [I]), and therefore uncertainty introduced by past emissions is very small. Lifetimes of N_2O and F-gases are longer, but their effect on RF is smaller. Therefore, the most important contributor of historical emissions with regard to current of future RF is CO_2 which is quite accurately known for the whole time period.

The most uncertain component of calculation of radiative forcing due to CO_2 is the estimation of removal from the atmosphere. Circulation of carbon dioxide between the atmosphere, the oceans and the terrestrial biosphere is a complex process, and therefore, the simple pulse response function of the REFUGE2 model (Eq. 2) yields uncertain results. Even when using large models describing circulation of CO_2 (complemented with atmospheric measurements), uncertainties are notable. For example, for the flux between atmosphere and the oceans in the 90's, the IPCC [2001a] estimates a value of -1.7 ± 0.5 PgC/yr (one σ) corresponding to an uncertainty of ±60% (2σ). Land-atmosphere flux in 1980's and 1990's was estimated by the IPCC to vary between -0.2 ± 1.4 PgC/yr and -1.4 ± 1.4 PgC/yr (2σ) depending on the time interval and literature source [IPCC 2001a]. This thesis does not deal with RF caused by emissions or removals in the LULUCF sector. The net impact due to global emission sources and sinks in terrestrial biosphere is quite poorly known, and probably close to zero.

Removal of other gases (CH_4, N_2O, F-gases) from the atmosphere is a simpler process, and it can therefore be more accurately estimated by using the functions of the REFUGE2 model. For all the gases, uncertainty in calculation of radiative forcing due to particular atmospheric concentration contains an uncertainty of around ±20% [IPCC 2001a, Section 6.3.4]. On the other hand, uncertainty in emissions was ±20% for CH_4, -40 to +100% for N_2O and -10 to +20% for HFCs, PFCs and SF_6 in 2003 (see Table 4). Therefore, for N_2O, estimated emissions are the most important source of uncertainty, whereas for other gases, more research is required for the identification of the most crucial calculation components for uncertainty. The methods to reduce uncertainty in emission estimates are discussed in more detail in Section 4.1.

When estimating future RF, the largest uncertainties are due to estimation of future emission development both globally and in Finland when long time scales (>50 years) are concerned. An insight in the range can be obtained by considering a range of scenarios [I]. As discussed in Article I, choice of global background concentration for future considerations affects results notably. In this thesis, the choice of background scenario was made based on the assumption that socio-economical and technological development are similar in Finland and globally, because it is not reasonable to assume that Finland would be isolated from the development in the rest of the world.

Uncertainties in the estimation of the absolute magnitude of RF are high, but they are substantially smaller when two points of time or two different scenarios are compared. This is due to a strong correlation between the estimates. In fact, when estimating forcing caused by a country or an activity, absolute value of RF is often less interesting than the results of different comparisons. [Sinisalo 1998; Savolainen & Sinisalo 1994]. Even though uncertainties in estimation of absolute RF caused by a country or an activity are high, REFUGE2 model forms a good means for comparison of different emission reduction policies.

4.2.2 GHG emission, removal and trend uncertainties for Finland

Uncertainties in GHG emissions and removals were estimated by using the KASPER model developed in this thesis. Lack of data created challenges for the estimation of uncertainty in individual input parameters. In nearly all the cases, expert judgement was needed in addition to other data sources, such as literature and measurement data. In general, estimation of statistical uncertainty can be done with more confidence than a bias estimation that is most often based on expert judgement and is thus always subjective to some extent. Degree of subjectivity is difficult to estimate, and is likely to vary from one emission category to another.

Bias (e.g. structural uncertainty of the models) is difficult to quantify and is often underestimated in uncertainty analyses. If calculation errors are detected, they are usually corrected before the assessment of uncertainty. In GHG inventories, models are usually quite simple, and the bias due to model structure is not likely to occur, and uncertainties can be satisfactorily assessed by

estimating uncertainties in each calculation parameter. There are exceptions, for example estimation of waste degradation in landfills, soil carbon stock changes and some categories in the agriculture sector. In these categories some important parts of emission generation process may be missing or may be erroneously modelled. This type of uncertainty cannot be fully detected by the type of uncertainty analysis presented in this thesis, even though some indication can be obtained using expert estimates.

In some categories included in the KASPER model, on-going and forth-coming research is likely to cause changes in the future. This is due to both the fact that the emission estimation will change, which leads to real differences in uncertainties, and because availability of better data will enable generation of more reliable uncertainty estimates. For example in categories CO_2 from peat production and CH_4 and N_2O from fuel combustion in large installations (CRF categories 1.A 1 and 1.A 2) more reliable uncertainty estimates may be obtained by using results of the on-going research projects described in Section 4.1.

Uncertainty estimates of emissions and removals in LULUCF categories presented in this thesis and in the National Inventory Report of Finland [Statistics Finland 2005] were carried out rather broadly. In these categories, more reliable uncertainty estimates could be gained by analysing possible causes of uncertainties in more detail and by integrating the uncertainty estimation to the calculation models.

Trend in GHG emissions or removals describes change in emissions or removals between two points of time (see Eq. 12). Therefore, trend estimate does not take into account the time series between the two points of time. Use of this definition may cause unillustrative trend figures in years with exceptionally high or low emissions or when a category is turning from sink to source, or vice versa. GHG emissions from Finland vary, e.g. due to climate conditions and availability of hydropower in the Nordic electricity market in a specific year [Statistics Finland 2005]. Therefore, perceptual trend figure, e.g. between 1990 and 2003 does not necessarily reflect the development of emissions during the whole time series from 1990 to 2003 (see Figure 9). Under the Kyoto Protocol, commitments are given for a five-year average (2008–2012). This gives a better insight in emission development than single year estimates. On the other hand, base year of the Kyoto Protocol (1990) is a single year estimate only, and

emissions in that year depended on many randomly varying factors. Therefore, interpretation of results of trend uncertainty has to be done carefully. Figure 9 reveals that net emissions from Finland vary largely between different years, and therefore also the share of a country of global emissions may depend on the year chosen for comparison. However, annual variation is smaller without LULUCF.

When estimating trend uncertainties, correlations between different years have a central role. The sensitivity study in Article II showed that trend uncertainty was largely dependent on the assumption of correlations. In the KASPER model, for most categories EF was assumed fully correlated across years, whereas activity data were estimated independent. This simple assumption has been recommended by the IPCC [2000a] and is used in most countries in uncertainty estimates of GHG inventories [e.g. Winiwarter & Rypdal 2001; Rypdal & Zhang 2000].

In addition to correlations catered by the KASPER model, it is evident that in the real world, uncertainties in emission estimates have different types of correlations that cannot be detected by the type of analysis used in this thesis. For example, activity data uncertainty may correlate in agriculture, if data collection methods are the same for many categories. On the other hand, correlations may occur, if emission factors, e.g. for different manure management systems used are taken from the same source or are based on the same data. Strength of these partial correlations is difficult to estimate.

Monte Carlo simulation was chosen as the method to combine uncertainties in the KASPER model. Monte Carlo simulation seems to be the most suitable means for this type of analysis, where models are complex, different types of correlations occur, and input parameters have non-normal distributions. In addition, largest uncertainties in this type of analysis are due to estimates of input parameter uncertainties, and therefore the choice of method to combine uncertainties is not likely to be any major issue for the output of the model.

For Monte Carlo simulation, uncertainty in each input parameter has to be described by using a PDF. Even though some general rules can be set as regards the choice of distribution, it is nevertheless difficult to estimate the shape of PDF based on expert judgement accurately, especially when uncertainties are large. The choice of distribution may have notable effect on results, as confirmed by a

sensitivity study performed in the agriculture sector, where large, asymmetrical uncertainties occur [IV]. However, when uncertainty in the total GHG inventory of Finland (without LULUCF) was considered, the majority of emissions came from sources with small uncertainties. For these sources, normal distribution is a good assumption, and it was shown in Article II that the choice of distribution did not have notable effect on the uncertainty of the total inventory.

Despite the uncertainty involved in an estimate of an absolute magnitude of uncertainty, all uncertainty estimates presented in this thesis were made as consistently as possible. Therefore, main attention should not be given to the absolute figures given for uncertainty, but for the differences in uncertainties between different categories. This is useful information when planning inventory improvements, and also when preparing new emissions trading schemes and emission reduction commitments.

The uncertainty analysis presented in this thesis for Finland covers all the gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and sectors of the Kyoto Protocol except removals under Articles 3.3 and 3.4. However, it is possible that the UNFCCC reporting requirements and guidance given by the IPCC do not yet cover all anthropogenic sources or sinks of GHGs. Potentially lacking anthropogenic sources (other than LULUCF) can nevertheless be assumed negligible. Uncertainty estimates of LULUCF categories Finland reported to the UNFCCC in 2005 are presented in Chapter 3 of this thesis. However, the Finnish 2005 Inventory did not yet cover all the LULUCF categories. When the coverage will be extended in future submissions, the need for uncertainty estimates of these categories will also rise.

In this thesis, uncertainties in GWP values (estimated at ±70% [IPCC 2001a]) were not taken into account. Under the UNFCCC, constant GWP values are used [FCCC 1999] and it was also decided that uncertainties in GWP values are excluded from uncertainty analyses of GHG inventories [IPCC 2000a]. Uncertainty in GWP values is a complex issue and depends on the chosen time scales, for example [Reilly et al. 1999]. Generally speaking, uncertainties in GWP values do not affect uncertainty estimates of emissions of each gas separately, but introduce uncertainty when emissions of different gases are summed up. Uncertainties in GWP values might thus change the weighting of different gases and affect the uncertainty in combined emissions.

4.2.3 Uncertainties in EU emissions trading schemes

In the estimation of uncertainties in different emissions trading schemes [III], uncertainties were estimated for EU-15 and EU-25 countries as a whole. For the estimation, e.g. uncertainties estimated by different member states were utilised. One option would have been to estimate uncertainties separately for each member state. In this case, random components of uncertainty could have partly cancelled each other out. But, it is likely that the bias is correlated across member states to some extent. This is due to use of similar methodologies, use of same emission factors (e.g. from IPCC guidance) and use of same data collection methods in some sectors (e.g. data used in agriculture may be based on the data provided for applying of agricultural subsidies). Again, estimation of correlations would have been very difficult, and therefore estimates were done at a more aggregated level.

Estimates of uncertainties in emissions trading [III] were largely based on current requirements for data quality, e.g. uncertainties in estimates of emissions from <20MW plants were assessed larger than uncertainties in >20MW plants. But, the situation may change due to requirements set in future emissions trading schemes.

Comparison between different emissions trading schemes was done based on uncertainties in corresponding inventories. This is not directly comparable to real uncertainties in emissions trading where emission allowances are exactly defined, and uncertainties are related to annual emission estimates of actors and to verification of the emissions. But, the approach used in Article III forms at least one basis for comparison of different schemes.

In the thesis, the share of EU-15 of global emissions is also assessed. Calculation of the share of Finland and the EU-15 of global emissions is uncertain. In addition to uncertainties in emission estimates themselves, comparability of the estimates used and unknown correlation between the two estimates introduces uncertainty to the results.

4.2.4 Comparison of uncertainty estimates with literature

One option to verify uncertainty estimates would be to compare them with empirical data. However, these kinds of data are scarce, and the type of verification is not possible in the case of most emission categories. In global scale, measured atmospheric concentrations of GHGs (complemented with inverse modelling) can be used for estimation and verification of emissions, but they are not applicable to allow conclusions on the associated uncertainty in emission estimates especially at the country level. For some gases (CO_2 and CH_4), it is difficult to distinguish between anthropogenic and natural sources. Uncertainties in the magnitude of natural GHG emissions may be much higher than those of anthropogenic emissions. In addition, atmospheric measurements give reasonable results only when rather large geographical areas are covered, and are therefore not suitable for the verification of emissions or uncertainty estimates of Finland.

Results presented in this study were compared with uncertainty estimates presented in literature and given by different countries in the National Inventory Reports collected and published by the UNFCCC [2004]. Table 10 provides information on uncertainty estimates from Annex I countries. For some Parties which have estimated uncertainty in national total, some categories are missing, typically LULUCF categories or F-gases.

Uncertainty estimates provided by Annex I Parties vary from ±2 to ±46% for total inventory, and from ±2 to ±19 percentage points for the trend. It is nevertheless difficult to compare uncertainty estimates of different countries. Firstly, interpretation of the concept 'uncertainty' may vary in different countries, e.g. extension of treatment of natural variability, possible bias and model error is likely to differ. Secondly, most uncertainty estimates of the GHG inventories are based on the IPCC guidance, and some Parties rely on estimates done in other countries when performing first quantitative uncertainty analyses. Therefore, uncertainty estimates given by different countries cannot be considered totally independent. Hence, if estimates are similar, it does not necessarily mean that real uncertainties in the countries compared are the same. On the other hand, it is unclear how differences in uncertainty estimates reflect real differences in accuracy or precision of emission estimates.

Table 10. Information on uncertainty estimates provided by Annex I Parties of the Kyoto Protocol in 2004 inventory submissions [UNFCCC 2004].

	Number of Annex I Parties
Annex I Parties	39
National Inventory Report provided	35
Quantitative uncertainty estimates provided[1]	25
Uncertainty in national total estimated	21
Tier 1 method used	15
Tier 2 method used	5

[1]This number includes all the Parties that have treated uncertainties in their NIR quantitatively. Some of them have only estimated uncertainties for some sectors/gases.

In 2004 submission, detailed Tier 2 uncertainty analyses, including estimates of uncertainty in national total, were provided only by Austria, Norway and UK in addition to Finland. These estimates were done at a rather detailed level and are well documented, and therefore considered to be comparable with the estimates provided in this thesis. Uncertainty estimates of Finland were compared with the estimates of above mentioned countries in Article II. Comparison made by gas revealed that estimated uncertainties in CO_2 and CH_4 were of the same magnitude in all the countries, but estimates of N_2O and F-gases varied. It was reported by Rypdal & Winiwarter [2001] that total inventory uncertainty in different countries is very sensitive to the assumption of uncertainty in N_2O from agricultural soils. This was also noticed in this study [II, III]. Differences in uncertainty estimates provided for this category in different countries are very likely due to subjective uncertainty assessment, rather than any real differences in uncertainties. This is a good example of the difficulty in estimating uncertainties in sources that are insufficiently understood.

In Article II, trend uncertainty in Finland was compared with other countries, and they were found to be rather similar when expressed as percentage points. However, the index used to measure trend uncertainty has to be carefully chosen before making comparisons. For example, qualitative considerations of Table 5 show that the UK is expected to have a decreasing trend and Norway and Finland an increasing one, but in the case of for Austria, emissions may decrease (according to 95% confidence interval), even though it is more probable that their emissions increase.

Only eight Parties provided quantitative uncertainty estimates of LULUCF categories in their 2004 inventory submission, and generally the estimates covered only a small share of the LULUCF categories (e.g. only liming). Uncertainty estimates for different categories varied from ±30 to ±60%, excluding liming, for which smaller uncertainties were reported.

Nilsson et al. [2004] stated that uncertainty in the Full Carbon Account (FCA) of forests can be estimated as accurately as ±4–5% (expressed as 90% confidence interval) for large areas. It was, however, stated that current models can not determine carbon sources and sinks with an acceptable accuracy at the regional or continental scale or interannual timescale. It was estimated that the interannual variability in FCA can be very high (2–3 fold for net primary production during 10–15 years time, due to, e.g. changes in weather and other disturbances), and therefore, uncertainties in FCA that is estimated for a single year only may be very high. Considering longer time periods was assessed as a strategy for reducing uncertainty in estimates. Another problem is to distinguish between human-induced and natural fluxes of carbon.

Vandenbygaart et al. [2004] estimated uncertainty in carbon stock of croplands. They estimated that a total of 5.7 TgC/yr was sequestered in cropland soils between 1991 and 2001 in Canada, with a range of 3.2–8.3 TgC/yr (within the 95% confidence interval). Ogle et al. [2003] estimated that agricultural soils in the US accrued 1.3 TgC/yr, with a 95% confidence interval from -4.4 to +6.9 TgC/yr. In terms of 95% confidence interval relative to the mean value, uncertainty estimated by Vandenbygaart et al. [2004] was around ±50% and by Ogle et al. [2003] some ±450%. It is, however, difficult to compare the results of these studies to estimates presented in this thesis, because models used for calculation are different, and therefore also the sources of uncertainties vary. In addition, perceptual interpretation of uncertainty may not suit well for categories which may act both as sinks and sources, because net emissions may be small when compared with uncertainties.

Due to difficulties in comparability, uncertainty should not be referred to as inventory quality, as concluded also by Rypdal & Winiwarter [2001]. Inside one inventory, however, the increase in inventory quality can be assessed by comparing uncertainties for different years. This can be done if uncertainty estimates are internally consistent between categories and between years.

Nevertheless, it has to be noted that category mix in different years is also an important contributor to the total uncertainty of the inventory, and therefore the results of uncertainty analyses should be carefully interpreted.

4.3 Contribution of the study

At the time of writing of the first uncertainty article [II], only few countries had carried out uncertainty estimates of their greenhouse gas inventories, and even fewer countries had done uncertainty analyses based on stochastic simulation. Since then, also other uncertainty analyses have been made by Annex I Parties of the Convention, but the uncertainty analysis presented in this thesis is unique in its detailed examination, coverage and treatment of correlations.

This thesis presented the first detailed uncertainty analysis for Finland based on stochastic simulation for the years 1990 and 2001, in addition to the latest results for the year 2003. This uncertainty analysis of the Finnish GHG inventory has already been used for reporting to the UNFCCC, planning inventory improvements and prioritisation of resources. The KASPER model developed in this thesis will be used by Statistics Finland in the forthcoming annual estimation and reporting of uncertainties in GHG inventories.

Internationally, the results presented in this thesis and the expertise developed in the course of the work have been used for the development of the IPCC 2006 Guidelines, which will give guidance for all the countries preparing GHG inventories. The results of this thesis will be included in the guidelines as examples. The expertise developed during the work has also been used when developing the uncertainty analysis of the EU GHG inventory.

The study shows that differences between uncertainties in different emissions trading schemes can be notable [III]. Results of the study can be used to compare pros and cons of different emissions trading schemes based on uncertainty in emissions to be included. These results can be utilised when planning future emissions trading schemes and potential verification procedures.

In the first Article of the thesis [I], REFUGE model that describes radiative forcing due to increased atmospheric concentrations developed earlier at VTT

was developed further. In the new model, REFUGE2, calculation of removal of CO_2, CH_4 and N_2O from the atmosphere was modelled more appropriately, by taking into account the effect of atmospheric concentration on the removal of the gases. In addition, F-gases (HFCs, PFCs and SF_6) were included in the model. In Article I, radiative forcing due to Finland's emissions by 2100 was estimated in different scenarios.

Both models (KASPER and REFUGE2) developed in the thesis and the results presented are useful for policy planning (e.g. for comparison of different emission reduction strategies or for planning of future climate commitments) and also for development of different indexes to estimate contribution of a country on climate change.

5. Conclusions

In this thesis, two different viewpoints of estimating country contributions to climate change are presented. First, radiative forcing model, REFUGE2 was developed, and radiative forcing due to Finland's emissions since 1900 was estimated. Greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and sectors (energy, transportation, industry, product use, agriculture, waste) covered are those of the Kyoto Protocol. Future forcing was estimated by using three different emission scenarios for Finland until 2100. The results show that radiative forcing caused by emissions from Finland was 3 mWm^{-2} in 1990 and will increase to 6–11 mWm^{-2} by 2100 depending on the emission reduction strategies applied and technological development. This corresponds to the share of 0.18% of global radiative forcing in 1990 and 0.13% in 2100, respectively. The decrease is due to expected increase in emissions from other counties (especially in developing countries). Uncertainty in radiative forcing was not assessed quantitatively. Absolute magnitude of radiative forcing is, nevertheless, estimated to contain rather large uncertainties. However, uncertainties in differences between various scenarios or different points of time are smaller than uncertainties in absolute magnitude of radiative forcing, because estimates are strongly correlated. Therefore, the REFUFE2 model is a useful tool for decision making when comparing effects of different emission reduction strategies.

Another viewpoint brought forth by the thesis was uncertainty in GHG emissions and how that affects the estimates of country contributions to the climate change. A stochastic calculation model for uncertainty in Finnish GHG inventory (KASPER) was developed in the thesis. Uncertainties in the Finnish GWP-weighted inventory were calculated for the latest inventory years (2001–2003) and for the base year of the Kyoto Protocol (1990). The results reveal that uncertainty in 2003 GHG emissions was -4 to +8% for inventory without LULUCF and -14 to +15% when LULUCF categories were included. In terms of absolute uncertainties, 95% confidence interval of Finland's GHG emissions (without LULUCF) in 2003 was 82–92 Tg CO_2 eq (mean value was 86 Tg). This corresponds roughly to the 0.2–0.3% share of global emissions. Finland's share of global emissions is thus at least twice the share of population (0.1% in 1990 and 2003). On the other hand, Finland's share of emissions is notably smaller than the share of global GDP, which was 0.4% in 2003 (0.6% in 1990). When

the share of emissions is compared with the share of radiative forcing, it can be seen that the share of radiative forcing is lower, due to Finland's relatively short emission history.

Uncertainty estimates are very sensitive to assumption of uncertainty in N_2O from agricultural soils. The estimation of uncertainty for this category, as well as the increasing of accuracy and precision of the emission estimates are challenging, because emissions occur in large geographical areas (continuous measurements cannot be used) and the emission generating processes are complex (good models are difficult to compile). We are faced with similar challenges with LULUCF categories, where carbon stock changes are important contributors to the uncertainty. It is in some cases uncertain whether a LULUCF category is a net sink or a net source.

Uncertainties in the Finnish inventory could be reduced e.g. by using continuous measurements in some sources (e.g. nitric acid production plants) and by making more research on emission categories related to agricultural soils (nitrous oxide emissions and carbon stock changes). However, reduction of uncertainty always carries a cost which is different for different categories and different types of uncertainties. Therefore, all uncertainties cannot be reduced, given current economic conditions and knowledge on processes affecting GHG sinks and sources.

Trend refers to change in net emissions between the base year (1990) and the latest inventory year (2003). In Finland, trend was 22% without LULUCF (95% confidence interval from 16 to 26%). With LULUCF, trend was 42% (95% confidence interval from 25 to 65%). Trend uncertainty is very sensitive to the estimated correlation between emission estimates of different years. To improve trend uncertainty estimates and comparability between different countries, more attention should be paid to assessment of correlations. Assessment of trend uncertainty also shows that when change in emissions between different years is small, also the direction of the change can be uncertain.

The results reveal that uncertainty in EU emissions trading scheme for CO_2 (2005–2007) contains rather small uncertainties (±3% based on uncertainties in inventories), but extension of emissions trading scheme to cover other sectors or gases is likely to increase uncertainties (up to -6 to +21% for Kyoto emissions

trading scheme with LULUCF). The share of EU-15 of global total emissions was estimated at 10–15%.

In 2004 inventory submissions, 25 Annex I Parties of the Kyoto Protocol provided quantitative uncertainty estimates of their GHG emissions and/or removals. Comparison of uncertainty estimates between different countries is difficult, because uncertainty estimates are always at least to some extent subjective, and because interpretation of the concept 'uncertainty' may vary. To enhance comparability between uncertainty estimates of different countries, it is essential to give clear guidance for uncertainty estimates, and to discuss differences between uncertainty estimates to be able to understand reasons behind them. It is also likely that superficial uncertainty estimates underestimate uncertainties, if all possible sources of uncertainties have not been detected. Due to difficulties in comparability, uncertainty should not be referred to as inventory quality.

Attention should be paid on communication of uncertainty, especially when uncertain quantities have economical values, as in emissions trading. Expressing uncertainties as 95% confidence intervals (corresponding roughly to 2σ) as in this thesis and recommended by IPCC may give a picture of larger uncertainties than intended, if the audience is used to communication of uncertainty as one standard deviation (σ) which is typical in scientific literature. In addition, expression of uncertainty as percent is not very illustrative for quantities that are differences between two almost equal quantities (e.g. growth and drain of forests). When the difference approaches zero, relative uncertainty approaches infinity. In addition, index used to measure trend uncertainty should be carefully chosen if different countries are to be compared.

Uncertainty analysis is a useful tool for planning improvements to emission inventories. Results of uncertainty analyses of GHG inventories and different emissions trading schemes should be taken into account when planning future emission reduction strategies. A limit for acceptable uncertainty could be set first, to participating countries (e.g. in emissions trading) and second, to categories included in climate commitments. Inclusion of highly uncertain emission categories in commitments is likely to be expensive, if large measurement campaigns are needed or much research is to be done for estimation and verification of emissions. On the other hand, if very uncertain

categories of removals (e.g. carbon stock changes in soils) are used to offset well known emission sources (e.g. CO_2 for fossil fuel combustion) there is a rather high probability of increasing net emissions, and in these cases real environmental benefits of climate commitments would become questionable. Therefore, future proposals for climate commitments should be carefully examined from the point of view of uncertainty.

6. Summary

Global warming occurs due to human-induced increase in atmospheric greenhouse gas concentrations. United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol were the first global commitments that aimed at reduction of anthropogenic greenhouse gas emissions. This thesis covers two aspects of the estimation of a country's contribution to the climate change. The first part of the thesis focuses on global warming effect caused by Finnish emissions from 1900 to 2100 in three different scenarios. The second part of the thesis concentrates on uncertainty of GWP-weighted emissions of a country. The thesis presents the first detailed uncertainty assessment of Finnish greenhouse gas inventory that was made using stochastic simulation to combine uncertainties. The study concentrates on the most recent inventory years (2001–2003), base year of the Kyoto Protocol (1990) and on future options for reducing uncertainties.

In the first part of the thesis, a model that describes radiative forcing caused by greenhouse gas emissions of a country was compiled. The model describes removal of greenhouse gases from the atmosphere by pulse response functions covering all greenhouse gases of the Kyoto Protocol: CO_2, CH_4, N_2O, HFCs, PFCs and SF_6. The model was used in the thesis to estimate forcing caused by Finnish emissions both in the past beginning from 1900, and also in the future, using three different emission scenarios. Sectors covered were energy, industry, transportation, agriculture and waste. According to the calculations, forcing caused by Finland will increase from 3 mWm^{-2} in 1990 to 6–11 mWm^{-2} by 2100 depending on emission reduction and energy saving strategies applied, and also on technological development. This was estimated to represent a share of 0.18% of global radiative forcing in 1990 and 0.13% in 2100. The reduction in share is due to expected increase in global emissions and consequently, in radiative forcing, especially in developing countries. When the choice of background concentration (atmospheric concentration caused by global emissions) was examined, largest difference occurred was 10% in forcing due to Finland in 2100. Sensitivity studies revealed that choice of modelling approach and estimation of global development of emissions should be paid attention when estimating warming effects caused by a single country or an activity.

The second part of the thesis presents assessment of uncertainty in Finnish GHG emissions, removals and trends. It also estimates how the uncertainty affects the estimated contribution of Finland to the climate change. Uncertainty assessment of Finnish greenhouse gas emissions inventory covered all gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and sectors of the Kyoto Protocol (energy, industry, transportation, product use, agriculture and waste). Uncertainties in removals under articles 3.3 and 3.4 of the Kyoto Protocol were also discussed, as well as uncertainties in the other categories reported by Finland to the UNFCCC under LULUCF (land use, land use change and forestry) in 2005. In the thesis, uncertainties were estimated based on measurement data, literature, expert estimates, and in many cases, on combinations of all three. Uncertainties were combined using stochastic simulation, i.e. Monte Carlo method. The results indicate that uncertainty in Finnish GHG inventory in 2003 (without LULUCF) was -4 to +8% (bounds of 95% confidence interval presented as percent relative to the mean value), which in turn indicates a range from 82 to 92 Tg CO_2 eq, with 86 Tg as the mean value. When LULUCF categories were included, uncertainty in the inventory was -14 to +15%, corresponding to a range from 58 to 78 Tg CO_2 eq with 68 Tg as the mean value. According to the results, Finland's share of global emissions without LULUCF was 0.2–0.3% when uncertainties in emissions were taken into account. Finland's share of global emissions is thus at least twice the share of population, 0.1%. On the other hand, Finland's share of emissions is smaller than the share of global GDP, which was 0.4% in 2003. When the share of emissions is compared with the share of radiative forcing, it can be seen that the share of radiative forcing is lower, due to Finland's relatively short emission history.

Carbon dioxide emissions from fossil fuel combustion covered over 80% of Finnish greenhouse gas emissions (without LULUCF) in 2003. These emissions are accurately known, because the amounts of fuel combusted and carbon contents of the fuels are well known. Emissions from some industrial processes releasing CO_2 are also accurately known, but other sources and sinks of greenhouse gases contain higher uncertainties. According to the results, the most important contributors to the uncertainty in Finland are N_2O emissions from agricultural soils, N_2O from nitric acid production, CH_4 from landfills and categories related to carbon stock changes in forests and agricultural soils. However, the inventory of LULUCF sector is not yet complete, and therefore the estimates have to be considered as preliminary. Of the most important emissions

and removals categories (in terms of uncertainty), nitric acid production is the only one where uncertainties can be rather easily reduced by installing continuous measurement instruments in plants, rather than by estimating emissions by calculations. For the other most important categories, reduction of uncertainty is rather difficult and costly, because emissions occur in large geographical areas that cannot be continuously measured. For these categories, uncertainties can be reduced by developing more detailed models for the estimation of emissions and removals, and by using representative measurement data for model parameterisation.

Trend of emissions (change in emissions from 1990 to 2003) was 22% increase without LULUCF and 42% with LULUCF. 95% confidence interval of trend indicated an increase from 16 to 26% without LULUCF, and from 25 to 65% with LULUCF, respectively. The assumption of correlations between the two years has a strong effect on trend.

The EU CO_2 emissions trading begun in 2005, covering the least uncertain emission sources (CO_2 from combustion in large installations and selected industrial processes). In the thesis, consequences of uncertainty on emissions trading were discussed by using examples of possible extensions of the EU ETS. In one example, EU emissions trading was extended to cover the same sectors as EU ETS (2005–2007), but also CH_4 and N_2O in addition to CO_2. In other cases, uncertainties in Kyoto emissions trading were assessed, both with and without land use change and forestry sector (Articles 3.3. and 3.4 of the Kyoto Protocol). The comparison revealed that EU CO_2 ETS (2005–2007) has rather small uncertainty (±3%) in the scale of EU-15 and EU-25 as a whole even though uncertainties between emission estimates of different actors is likely to vary. Inclusion of CH_4 and N_2O from the same sectors would increase tradable amount of emissions only by 2%, but the uncertainty in the emissions would increase to (-4 to +7%). However, this example was a merely hypothetical illustration of the effect of inclusion of these gases into the trading scheme. Uncertainty in Kyoto emissions trading would be much larger, but because removals under articles 3.3 and 3.4 of the Kyoto Protocol are estimated to be small in the EU-15 in Kyoto period, inclusion of these sources would not affect the uncertainty notably (uncertainties in Kyoto emissions trading scheme both with and without LULUCF were up to 21%). In emissions trading, it is important to estimate

uncertainty of emissions of both purchasers and vendors, to avoid increase in net emissions.

Uncertainty estimates presented in this thesis can be used to improve inventory, to assess reliability of emission estimation methods, and to plan future environmental commitments. Understanding uncertainty is important in decision making to ensure that climate conventions are of real benefit in terms of mitigating climate change. In addition, radiative forcing model developed in this thesis can be used for decision making and when comparing different emission reduction strategies.

7. Publications and author's contribution

The thesis consists of four articles, of which the author of the thesis was the responsible author. Each article and the author's contribution are described below.

I. Radiative forcing due to anthropogenic greenhouse gas emissions from Finland: methods for estimating forcing of a country or an activity

The aim of Article I was to estimate radiative forcing caused by a country or an activity that causes only a small share of global radiative forcing. The author of the thesis developed the REFUGE2 calculation model. The model was programmed by the author from the beginning, but it was based on a former model REFUGE developed earlier at VTT by using a different programming language. The current version was based on latest scientific understanding presented by the IPCC [2001a] on removal of gases from the atmosphere and on radiative forcing caused by increase in atmospheric concentration. In addition, radiative forcing due to emissions of F-gases was included in the model, and removal of CO_2 from the atmosphere was modelled in more detail, taking into account different concentration levels in the atmosphere. Feedbacks of methane and nitrous oxide on their lifetimes in the atmosphere were included in the new version of the model, and global background concentration was taken into account for estimation of RF caused by a single actor only. The two possibilities to estimate RF by a country or an activity (marginal and average forcing approach) were proposed by a co-author. Data acquisition and calculation of the results were made by the author under the guidance of the co-authors. In Article I, the author was responsible for sections describing methods, scenarios and results. Discussion and conclusions were written jointly with the co-authors.

II. Uncertainties in the Finnish greenhouse gas emission inventory

Article II describes the very first detailed uncertainty assessment done for the Finnish GHG inventory based on stochastic simulation. The author of the thesis compiled the uncertainty calculation model and was responsible for the estimation of uncertainty of different input parameters. Literature surveys were conducted and many experts were interviewed in order to estimate input

parameter uncertainties. The author calculated the results for Article II and wrote other chapters except Introduction and Discussion and conclusions that were written jointly with the co-authors. Later on, the importance of uncertainty in CH_4 and N_2O emissions on total inventory uncertainty, especially the importance of CH_4 from landfills was discussed in a conference publication [Monni et al. 2003]. However, the publication was not included as one of the original publications of the thesis because it was rather short and superficial, due to length requirements set by the conference.

Article II described uncertainties estimated for the years 2001 and 1990. Uncertainty analysis of the Finnish GHG Inventory has been updated annually since then. For 2002 and 2003 inventory uncertainty estimates, some changes were made that are described in Sections 1.5 and 2.3 of the thesis. The results that reflect the current knowledge and official GHG Inventory Reporting of Finland to the UNFCCC are presented in Chapter 3 of this thesis.

III. Comparison of uncertainty in different emission trading schemes

In Article III, uncertainties in different emissions trading schemes were compared, based on uncertainties in corresponding inventories. The author of the thesis developed the calculation model used for estimation of uncertainty and estimated uncertainties in each emission category at the EU level. The author was also responsible for calculating the results and for writing the other chapters except Introduction and Discussion and conclusions that were written jointly with other authors. Extended version of the paper is to be published in *Water, Air, & Soil Pollution: Focus (WAFO)* together with other papers from the conference.

IV. Uncertainty in agricultural CH_4 and N_2O emissions from Finland – possibilities to increase accuracy in emission estimates

Agriculture is an important contributor to uncertainty in GHG inventories. The sector includes the most uncertain GHG emission source in many countries – N_2O from agricultural soils. In addition, agriculture is an interesting category, because natural variability is large and emissions occur in large geographical areas. Therefore, in Article IV, uncertainties in agriculture were assessed in more detail than in Article II. The author of the thesis was responsible for the

compilation of uncertainty estimation model based on an emission estimation model used by the co-authors. The author was responsible for data acquisition for uncertainty estimates and for the calculation of the results. The author was responsible for writing the Sections 1, 2 (except Section 2.1 and the text on N_2O from agricultural soils in Section 2.4), and 3. Chapter 4 was written jointly with the co-authors. The results presented in Article IV are somewhat different from those presented in Article II due to a more detailed examination. The results presented in Article IV are included in the latest version of uncertainty calculation that is reported in Chapter 3 of the thesis.

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Estimation of country contributions to the climate change
Viewpoints of radiative forcing and uncertainty of emissions

Abstract

Global warming that occurs due to emissions from a country or a country group was studied from two different points of view. Firstly, warming effect caused by Finnish emissions was assessed by a radiative forcing model. Secondly, uncertainty of GWP-weighted emissions from Finland was assessed using stochastic simulation to combine the uncertainties. In addition, uncertainties in different emissions trading schemes were compared at EU level. Consideration covered the gases (CO_2, CH_4, N_2O, PFCs, HFCs and SF_6) and sectors (energy, industry, transportation, agriculture and waste) of the Kyoto Protocol. Land-use, land use change and forestry (LULUCF) was covered more superficially. Finnish greenhouse gas emissions in 2003 were 86 Tg CO_2 eq (without LULUCF). According to the results, 95% confidence interval of this figure lies between 82 and 92 Tg CO_2 eq. This represents a share of 0.2–0.3% of global emissions. In the same year, Finland's share of global population was 0.1% and share of global GDP 0.4%. The inclusion of LULUCF categories in the inventory increased the uncertainty of net emissions notably. According to the radiative forcing calculations, forcing caused by Finland will increase from 3 mWm^{-2} in 1990 to 6–11 mWm^{-2} by 2100, depending on emission reduction strategies applied and technological development. Thus, Finland's share of global radiative forcing was 0.18% in 1990 and will decrease to 0.13% by 2100. In emissions trading it was concluded that uncertainty in the EU emissions trading scheme for CO_2 (2005–2007) contains rather small uncertainties, but the extension of emissions trading scheme to cover other sectors or gases is likely to increase uncertainties. Both radiative forcing and uncertainty assessment models can be used for comparison of different emission reduction strategies and planning of future climate commitments.

Keywords
climate change, global warming, radiative forcing, emissions, greenhouse gases, estimation, modelling, emissions trading, emissions reduction

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