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ESTIMATION OF GREENHOUSE IMPACTS OF CONTINUOUS REGIONAL EMISSIONS

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VTT Energy

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Abstract

In this thesis a method to calculate the greenhouse impact of continuous, time-dependent, non-global greenhouse gas emissions is used to estimate the impact of estimated anthropogenic pre-1990 and future (post 1990) emissions of CO_2, CH_4 and N_2O of Finland and Nordic countries. Estimates for the impact of Finnish CFCs and their substitutes and the significance of Finnish forests as carbon sink are also calculated. The method is also used to compare several different wood and peat energy production schemes with fossil fuel use, in terms of caused greenhouse impact. The uncertainty of the results is examined.

The greenhouse impact is measured in this thesis as the global mean direct radiative forcing caused by the emissions. Radiative forcing is the driving force behind the climate change and as such it can be used to assess the ensuing climate change. The method is suitable for greenhouse agents that can be considered to be well mixed in the atmosphere (mainly CO_2, CH_4, N_2O and both CFCs and their substitutes).

According to the results Finnish greenhouse impact due to anthropogenic CO_2, CH_4 and N_2O emissions has increased eight-fold during this century, and will very likely remain higher than current level throughout the next century. The impact of Nordic countries has followed the same general pattern as Finland. It is likely that the per capita radiative forcing of the Nordic countries will remain above the global average.

The uncertainty of the absolute results is quite high due to uncertain knowledge at several stages of the calculation. When the results are used in comparisons (e.g. between emission scenarios, or emissions of different countries), the accuracy of the results increases considerably.

Preface

This work was carried out in VTT Energy during the years 1990 - 1996. Parts of it have been financed by the Nordic Council, the Finnish Ministry of Trade and Industry (KTM), and the Finnish Ministry of the Environment (YM).

I owe my thanks to professor Markku Kanninen, Dr. Kari Hillebrand and Mr. Ismo Nousiainen helpfully shared their knowledge of forests and forestry.

I wish to express my gratitude to Ilkka Savolainen, the senior researcher and leader of our small group, whose advice and insights were crucial to the work. Dr. Riitta Korhonen provided guidance and ideas in the early parts of this work, and Mrs. Riitta Pipatti has been helpful in many occasions concerning greenhouse gas emissions.

Special thanks are due to professor Raimo P. Hämäläinen, whose personality had a role to play when I chose applied mathematics as my field of study.

I wish to thank my parents Timo and Anja Sinisalo, and my godmother Soili Sinisalo for the support they have given. Last but not least I thank my wife Petra Laurema for patience and love.

Espoo, March 1998

Jukka Sinisalo

Contents

Appendices of this publication are not included in the PDF version. Please order the printed version to get the complete publication (http://www.inf.vtt.fi/pdf/publications/1998/)

List of publications

This dissertation is based on the following eight publications referred to by roman numerals [I - VIII] in the text:

I Korhonen, R., Savolainen, I. and Sinisalo, J. 1993. Assessing the impact of CO_2 emission control scenarios in Finland on radiative forcing and greenhouse effect. Environmental Management Vol. 17, No. 6, pp. 797 - 805.

II Kanninen, M., Korhonen, R., Savolainen, I. and Sinisalo, J. 1994. Comparison of the radiative forcings due to the CO_2 emissions caused by Fossil Fuel and Forest Management Scenarios in Finland. In: Kanninen, M. (ed.). Carbon balance of world's forested ecosystems: towards a global assessment. Proceedings of the IPCC AFOS Workshop held in Joensuu, Finland, 11 - 15 May 1992. Publications of the Academy of Finland 3/93. pp. 240 - 251.

III Pipatti, R. and Sinisalo, J. 1994. Scenarios for halocarbon emissions in Finland and estimates of their impact on global warming and chlorine loading in the stratosphere. Journal of Environmental Management 40, pp. 259 - 275.

IV Savolainen, I. and Sinisalo, J. 1994. Radiative forcing due to greenhouse gas emissions and sinks in Finland - estimating the control potential. The Science of the Total Environment 151, pp. 47 - 57.

V Savolainen, I., Hillebrand, K., Nousiainen, I. and Sinisalo, J. 1994. Comparison of radiative forcing impacts of the use of wood, peat, and fossil fuels. World Resource Review, Vol. 6, No. 2. pp. 248 - 262.

VI Pipatti, R., Savolainen, I. and Sinisalo, J. 1996. Greenhouse impacts of Anthropogenic CH_4 and N_2O emissions in Finland. Environmental Management, Vol. 20, No. 2. p. 219 - 233.

VII Sinisalo, J. and Savolainen, I. 1996. Radiative forcing caused by anthropogenic greenhouse-gas emission histories of the Nordic countries. Ambio, Vol. 25, No. 3, pp. 185 - 190.

VIII Sinisalo, J. and Savolainen, I. 1997. Stabilization of the greenhouse impact caused by anthropogenic emissions from the Nordic countries. Journal of the Air and Water Management Association Vol. 47, No 7. pp. 806 - 810.

The author of this thesis had the following contributions to the articles:

I The author of this thesis participated in the development of the REFUGE model and he designed and coded the computer program. He estimated the past Finnish fossil CO_2 emission, performed the actual calculations to obtain the results and finally took part both in the scenario development and analysis of results.

II The author of this thesis took part in both the construction of the forest scenarios and the analysis of the results, and performed all the calculations.

III The author of this thesis added the halocarbon system for chlorine loading into the REFUGE model and performed the radiative forcing and chlorine loading calculations, and took part in the analysis of the results.

IV The author of this thesis estimated the emission histories for CH_4 and N_2O, implemented CH_4 and N_2O radiative forcing calculations to the computer program, performed all the calculations and the uncertainty studies and took part in the construction of the future scenarios and analysis of results.

V The author of this thesis had a role in the formulation of the time-dependent greenhouse gas emissions and sinks due to energy production, calculated the resulting radiative forcings, performed some sensitivity studies on the main results and took part in the analysis of the results.

VI In this study the author of this thesis calculated the radiative forcings due to the emission scenarios and took part in the analysis of the results.

VII In this article the author of this thesis has generated the estimates on the emissions, calculated the radiative forcings and per capita radiative forcings, compared emission estimates for year 1990 arrived at with values from other sources and took part in the analysis of the results.

VIII In this article the author of this thesis devised the future scenarios of the emissions, discussed the reasoning behind them and performed all the calculations. With Ilkka Savolainen he decided upon the per capita approach of the greenhouse impact entitlements and analyzed the results.

1. Introduction

1.1 The greenhouse effect

The natural greenhouse effect is a well-known phenomenon that increases the average surface temperature of Earth by some 33 °C from the temperature it would have without an atmosphere. The temperature increase is due to the presence of so called greenhouse gases in the atmosphere: without them the climate of Earth would resemble that of Mars. The main natural greenhouse gases in the atmosphere are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The effect of greenhouse gases can be understood in terms of energy balance: energy arrives at Earth from sun mainly by short-wave radiation (ultraviolet and visible light) and leaves Earth as long-wave (infrared) radiation. In a steady state both incoming and outgoing energy flows must be equal.

Increasing atmospheric concentrations of greenhouse gases due to human activities increase the atmospheric absorption of the outgoing infrared radiation but not the incoming short-wave radiation, and thus disturb the energy balance of incoming and outgoing radiation. As a result the average temperature of the Earth rises until the outgoing infrared radiation, which increases when temperature increases, once again equals the incoming radiation. Intergovernmental Panel on Climate Change (IPCC) has published several extensive reports on the subject of climate change. Especially IPCC (1990;1995;1996) provide clear and well presented material assessing the available scientific evidence.

Accurate direct measurements of the atmospheric concentration increases are available for some decades; the earlier concentration trends have been estimated from ice core data (CDIAC 1994). CO_2 concentration has increased from "background" levels by 30%, CH_4 by 145% and N_2O by 15%.

In the global scale experiments can not be carried out on the mechanisms and impacts of the human interference with the climate system. Thus mathematical models must be employed for projections of future developments. General Circulation Models (GCMs) may be used to produce estimates of climatic variables given the atmospheric concentration increases or emissions. These results may then be used to drive other models describing the impacts of climate change (temperature, rainfall etc.) on ecosystems and society. Economic models may then be further applied in order to estimate the impacts of projected climatic changes on exposure units (e.g. national and global economies) (IPCC 1994). The farther the modeling effort moves from actual physical quantities, the more uncertain become the theory, methods, results and conclusions. Integrated systems models attempt to integrate the causes, impacts, feedbacks and policy implications of the greenhouse problem (e.g. Alcamo 1994).

A large part of current scientific effort in the field of climate change is directed towards future global climate prediction, measurements of key climatic variables and future impact estimation (IPCC 1996). If global emission reductions are to be expected, all individual agents must also be prepared to control their greenhouse gas emissions (SILMU 1996). Thus tools for the evaluation of the impacts of non-global emissions on climate change must be available for the determination of rational climate change mitigation policies on a regional scale.

Radiative forcing calculations are one such tool but they have been previously used in connection with global emission scenarios. Only one quite coarse method - Global Warming Potentials (GWP) (Lashof and Ahuja 1990) - is in wide use for the estimation of the impacts of non-global emissions (e.g. Rodhe et al. 1991, Finland 1995; Norway 1995). In this thesis radiative forcing calculations are used to measure the impact of local emissions.

1.2 Radiative forcing of a greenhouse gas

The greenhouse impact of a greenhouse gas emission depends both on the time dependency of the concentration perturbation caused by the emission and on the gas-specific change in the radiation energy balance caused by the concentration change. Global average direct radiative forcing (simply radiative forcing in the following) of a greenhouse gas emission may be modeled by separately calculating the concentration change due to an emission as a function of time and the radiative forcing caused by said concentration change. This way it is possible to take into account the changes in the global concentration levels. Radiative forcing is a quantitative measure of the perturbation of the energy balance of the Earth - the driving force behind the greenhouse impacts.

1.2.1 Radiative forcing caused by a concentration change of a greenhouse gas

The disturbance in the radiation balance (radiative forcing) due to a change in a trace gas concentration is calculated with so called radiative transfer models (e.g. Ramanathan 1976). They model the absorption, emissions and scattering of radiation energy in the atmosphere and take into account the different absorption spectra of the main atmospheric gases, clouds etc. According to my knowledge the radiative forcing due to increases in greenhouse gas concentrations has not been directly measured yet due to difficulty of measurements and because the radiation balance has relatively large natural variation. Thus for the time being it is a theoretical measure, relying on mathematical models that relatively accurately reproduce the current radiative balance of the earth. However the human influence on climate has been (tentatively) detected in some recent results (Santer et al. 1996).

In the calculation of global average radiative forcing the results of aforementioned models are averaged over the whole globe, and relatively simple relationships between concentration changes and caused average radiative forcing are sought (Wigley 1986). Due to being global average, it is suitable only for greenhouse agents that can be assumed to well mixed in the atmosphere. The functional form of radiative forcing depends on the relative saturation of radiation absorption, and thus on the global concentration level of the gas under consideration. For relatively high concentrations (hundreds of ppm_v) the radiative forcing has a logarithmic, for moderate concentrations a square-root and for low concentrations (a few ppb_v) a linear dependence on the concentration change (e.g. IPCC 1995). The calculated radiative forcing does not depend on the path taken to reach a certain concentration level, only on the initial and final concentrations.

The precision of the radiative forcing functions is estimated to be approximately ± 20 % due to several types of uncertainty. Differences in the details of the radiative transfer modeling causes an estimated uncertainty of ± 10 %. Furthermore, the assumptions made in the radiative models in the assumed or computed vertical profile of the concentration change, temperature and moisture; assumptions with regard to cloudiness, assumed concentrations of other trace gases and indirect effects causes an uncertainty of at least ± 10 % (IPCC 1990).

Some greenhouse gases like CH_4 and CFCs not only affect the radiative balance themselves (direct radiative forcing), but they also cause changes in the atmospheric chemistry that affect the radiative balance (indirect forcing). For example when destroyed chemically in the atmosphere methane creates water vapor, and the chlorine released by the destruction of CFCs acts as a catalyst in a reaction that destroys stratospheric ozone, which is also a greenhouse gas. The impacts of these so called indirect effects are not as well known as the

direct ones; in some cases (e.g. O_3) the indirect effect may be of the same order of magnitude as the direct effect.

1.2.2 Atmospheric concentration of a greenhouse gas

The radiative properties of a greenhouse gas do not alone define the effectiveness of a greenhouse gas emission: the speed at which the emitted gas is removed from the atmosphere is another key factor. Thus a radiatively effective gas (e.g. CH_4) that is removed from the atmosphere relatively quickly may still be less effective as a greenhouse gas in the long run than a radiatively weaker gas that stays in the atmosphere longer (e.g. CO_2).

One way to describe the carbon cycle is to use compartment models, where the relevant parts of atmosphere-ocean system are divided into compartments, within which CO_2 is assumed to be evenly distributed. The most important components are the atmosphere, mixed layer of the oceans and the deep sea. Mixed layer is the topmost layer of the oceans down to approximately 50 m, that can be assumed to be well mixed.

Three- and two-reservoir (compartment) models were first suggested by Houtermans et al. (1973) for ^{14}C concentration response calculations. Later compartment models have been developed that take into account advection, eddy diffusion (e.g. Oeschger et al. 1975) and the variation of vertical transport rates with latitude (Siegenthaler and Joos 1992). These models are calibrated using both steady state calculations for pre-industrial values and the measured bomb-produced ^{14}C-distribution data of the oceans. They result in non-linear ordinary differential equation systems. In some models the biosphere is also included with some compartments, to take into account the changes of the carbon storage in the terrestrial biosphere, e.g. the possible CO_2 fertilization effect (e.g. Siegenthaler and Oeschger 1987).

Another, more complicated method is the use of ocean-GCMs, where the interactions are modeled with three-dimensional ocean current models (e.g. Maier-Reimer and Hasselmann 1987; Sarmiento and Orr 1992). In the model the carbon exchange between the ocean and atmosphere is determined directly from the (temperature-dependent) chemical interaction rates in the mixed layer. The carbon is transferred into deeper ocean due to fixed three-dimensional ocean circulation. In the form used the model contains essentially no free tuning parameters.

The two different modeling approaches outlined above result in similar estimates for the transfer of atmospheric C into the deep ocean, which seems to indicate that the description of ocean processes is reasonably valid, especially because the second model type contains essentially no tunable parameters.

The other greenhouse gases apart from CO_2 are removed from the atmosphere by chemical reactions that are slow compared to the atmospheric transport of the molecules. Thus the gases can be considered to be well mixed, and the changes in atmospheric concentration levels due to emissions may be approximated by an ordinary differential equation

$$\dot{C} = -\alpha C + E(t) \qquad (1)$$

where α is the inverse of the atmospheric adjustment time of the gas and $E(t)$ is the emission at time t. For most of the gases the atmospheric adjustment time equals the lifetime, but for methane the adjustment time is somewhat longer than the lifetime[1].

[1] Lifetime of the gas is defined as the time it takes for the concentration due to a small emission pulse to decrease to 1/e:th of the initial (maximum) concentration level. Adjustment time takes into account possible feedbacks due to the increasing concentration.

Nitrous oxide adjustment time estimates are the result of two-dimensional stratospheric chemical transportation models that include the accurate modeling of transmission of ultraviolet sunlight. Similar results have been reached with 3-dimensional transport model considerations. According to current estimates the lifetime of N_2O in the atmosphere is approximately 120 years with no announced uncertainty (IPCC 1996). The independently estimated N_2O fluxes and lifetime are inconsistent with the observed atmospheric concentration change. The estimated lifetime for N_2O has decreased during the last 6 years from 150 (IPCC 1990) to 132 years (IPCC 1995) and then from 132 to 120 years (IPCC 1996).

The methane adjustment estimate is based on estimates about several loss processes. Methane is removed from the atmosphere by reaction with tropospheric OH, stratospheric photolysis, oceanic uptake, destruction at the land surface, other losses in the troposphere and removal by precipitation. In practice only atmospheric chemistry is taken into account, which results according to global atmospheric chemistry models in an estimated lifetime of 8.5 years. Because CH_4 strongly affects it's own lifetime via a highly coupled CH_4-CO-OH system, an atmospheric adjustment time is used instead of lifetime, when the effects of methane concentration perturbations are considered. The feedback increases the chemical lifetime of methane resulting in an adjustment time of approximately 12 years with an uncertainty of $\pm$ 25% (IPCC 1996). As with N_2O, the estimated methane fluxes and adjustment time (IPCC 1996) are inconsistent with each other.

The adjustment estimate of CFC-11 is "not based solely upon model calculations, but use information from measurements to better constrain the lifetimes of theses and other gases" (WMO 1994). The lifetimes for the other CFCs, HCFCs and substituting compounds are normalized using the estimate for CFC-11, which has an uncertainty of $\pm$ 10 %.

The removal process of methane oxidizes methane into carbon dioxide in the atmosphere, so depending on the case it may be that also the greenhouse impact of the resulting CO_2 ought to be calculated. Usually the CO_2 is in some way already accounted for, but for example in the transportation of natural gas via pipelines the leakage of CH_4 is significant, and in this case the transformation of CH_4 into CO_2 should also be taken into account. In the short term the effect of the inclusion is minor, because methane is much stronger than CO_2 on per molecule basis, but in the long term the estimate for even the total impact (integrated radiative forcing) of the CH_4 emission may increase by some 15 % if the oxidization effect is included[2].

1.3 Global warming potential

Global warming potentials (GWP) are widely used to compare the impacts of greenhouse gas emissions with each other (e.g. Rodhe et al. 1991, Finland 1995, Norway 1995). Global warming potential represents the average strength (radiative forcing) of a greenhouse gas during a certain period of time, scaled so that the strength of CO_2 is always unity. GWPs are typically given for 20, 100 and 500 year intervals (e.g. IPCC 1990), where 20 years is considered to represent the short-term, 100 years the medium term and 500 years the long term impacts.

Because GWPs are derived from radiative forcing, they suffer from the same uncertainties as mentioned previously in connection with radiative forcing (uncertainties of concentration and radiative forcing calculations). Some additional difficulties are associated with the use of GWPs. For example, the GWPs of relatively short-lived trace gases such as CH_4 are very sensitive to the integration period selected. Another problem with integration periods is that the effects of the greenhouse gases beyond the time horizon are implicitly ignored.

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[2] GWP_{CH4}(500 a) = 6.5, GWP_{CO2}(500 a) = 1 (IPCC 1996).

Furthermore, the use of GWPs condenses all future impacts into one number by integration. This means that the dynamic aspect of the phenomenon is lost. If the dynamic behavior of the gases is ignored, it means (among other things) that in the results the total impact of the emissions of one year is concentrated on the same year. In other words, when the emissions of each year are multiplied by the appropriate GWP factor, the effect of the differences between the lifetimes of the gases is ignored, and the effect of either an increase or a decrease in emissions is overestimated. This is illustrated in Fig. 1, where the impacts of emission pulses are estimated both by calculating the radiative forcing and by using the GWPs (100 a).

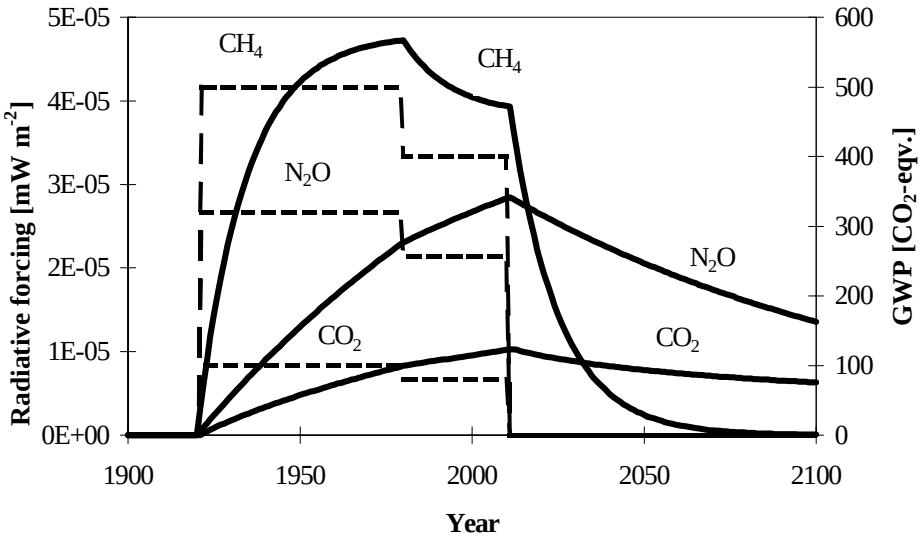

Fig. 1. Radiative forcing (solid lines, left axis) and Global Warming Potentials (dashed lines, right axis) of emissions of CO_2, CH_4 and N_2O. The emissions start at 1920 and decrease by 20 % at 1980, ceasing altogether at the year 2010 (i.e. exactly as the GWP values do). The (maximum) emissions levels used in the calculations are 100 Mg CO_2, 20 Mg CH_4 and 1 Mg N_2O.

For methane the GWP values give a reasonable approximation of the impact, but not so for the other gases. For CO_2 and N_2O approximately half of the

actual impact occurs after the emissions and the GWP-estimated impacts have already ended.

In practice GWPs give qualitatively similar results to radiative forcing calculations in cases where the emissions are strongly increasing, because in such a case the greenhouse impact due to emissions is dominated by the most recent emissions. The difference between the two impact estimation methods becomes more important when for example the effectiveness of attempted emission reduction strategies are examined.

1.4 Objectives and structure of the study

The main objective of this work is to estimate the greenhouse impact caused by local greenhouse gas emissions. First a calculation model is devised to calculate the greenhouse impact - measured as global average radiative forcing. Then the ways used to produce the emission estimates to be used as input for the model are shown. One approach to the uncertainty of the results is also presented. The next section concentrates on the results and the uncertainties of two specific cases. Finally the results are discussed and some final conclusions drawn.

2. Methods and materials

2.1 The model (REFUGE)

REFUGE is a computer program (Sinisalo, 1993) built to calculate global average radiative forcing due to a greenhouse gas emission. First the emissions are converted into atmospheric concentration change, and then the radiative forcing due to the concentration change is calculated. The same approach has been used in MAGICC (Hulme et al. 1995).

2.1.1 CO_2 concentrations

In the REFUGE model the concentration change caused by emissions is calculated for CO_2 mainly with a convolution integral

$$C(t) = C_0 + \int_{t_0}^{t} f(t-\tau)E(\tau)d\tau \qquad (2)$$

where C_0 is the original CO_2 concentration, $\boldsymbol{E(\tau)}$ represents the CO_2 emissions at time $\boldsymbol{\tau}$ and $\boldsymbol{f(t)}$ is a pulse-response function that has been derived from detailed carbon cycle models. Pulse response function describes the amount of excess carbon dioxide left in the atmosphere after time t of the original emission. In the calculations of this thesis the pulse response function

$$f(t) = 0.131 + 0.201e^{-t/362.9} + 0.321e^{-t/73.6} + 0.249e^{-t/17.3} + 0.098e^{-t/1.9} \qquad (3)$$

has mostly been used (Maier-Reimer and Hasselmann 1987). It has been derived from an emission pulse that rises the atmospheric concentration from a pre-industrial level to current level. One good property of this approach is that the pulse response function can be easily adapted, allowing easy employment of

the results of different carbon cycle models (e.g. Stocker et al. 1994; Sarmiento and Orr 1992) and simulation of the effects of uncertainty.

The transfer of atmospheric carbon into the oceans becomes relatively slower when the atmospheric concentrations increase. Thus the used pulse response function tends to overestimate the concentration increase caused by past emissions and underestimate the impact of future emissions. On the other hand the model of Maier-Reimer does not take into account either the ”biological pump” in the northern Atlantic or the assumed carbon fertilization of a biospheric sink (Siegenthaler 1983; Maier-Reimer and Hasselmann 1987). These omissions cause the model to underestimate the removal of CO_2 from the atmosphere. Thus the concentration calculations for CO_2 are most probably conservative in the sense that for some CO_2 emission the calculated concentration change is higher than the actual change.

Two three-compartment models (atmosphere, surface layers and deep sea) are used in [I] to calculate approximate upper- and lower bounds of the concentration changes caused by CO_2 emissions. Otherwise [II] - [VIII] the pulse response (eqs. 2 - 3) approach is used to calculate the concentration changes. The compartment model from Siegenthaler (1983) has also been implemented and verified to reproduce the observed concentration history with an input of estimated emission history based on Siegenthaler and Oeschger (1987), but it has not been actually used for application calculations, because the pulse-response approach works just as well in the context of this thesis and is more easily modifiable.

2.1.2 Other trace gas concentrations

For other greenhouse gases the concentration changes are calculated with eq. (1). The values of α are selected from literature, mainly IPCC reports (e.g. IPCC 1996), so they occasionally vary somewhat between the articles of this

thesis, because best available estimates have changed during the span of the articles.

2.1.3 Radiative forcing due to concentration change

The functional forms used in REFUGE were originally proposed in Wigley (1986), with original coefficients derived from the results of Kiehl and Dickinson (1987) for CO_2 and CH_4, and from Ramanathan et al. (1985) for N_2O and CFCs. Later the coefficients have been improved in Hansen et al. (1988) and further clarified in IPCC (1990). The functions used in this thesis have been taken from IPCC (1990) and are still considered valid by more recent reports (IPCC 1995;1996) although the radiative forcing caused by methane may be underestimated by up to 20 % (Lelieveld et al. 1993). This has not been certain, however, so it has not been taken into account in the articles of this thesis.

Due to the considerable uncertainty associated with the indirect effects of the emissions, only direct effects on the radiative forcing have been taken into account in this thesis, with the exception of methane in the most recent articles [VII - VIII], where indirect effects have been included by multiplying the radiative forcing of methane by 1.3 (IPCC 1995).

In the publications included in this thesis, the global background concentrations have been assumed to remain at current (1990) levels when the effects of the (relatively small) Finnish emissions are estimated. Because the radiative forcings of CO_2, CH_4 and N_2O all have less than linear dependence on concentration, and the global concentrations will very probably increase (e.g. Enting et al. 1994; Richels et al. 1996), this causes inevitably an overestimation of some 10% of the radiative forcing in the next century.

Since the future global concentration development is not well known and because the results of the calculations are not meant to be used to predict

impacts but to compare impacts of different scenarios, it is sensible to choose some set concentration development that is used for all cases, even though the Finnish future scenarios most likely depend on the global level decisions that influence the global concentration development.

2.2 Estimation of greenhouse gas emissions

In order to be able to use any model to estimate the impact of the emissions, the emissions themselves must be first estimated. For obvious reasons there was no interest in reporting statistics on the emissions of such unimportant trace gases as CO_2 and methane before the possibility of climate change was fully realized, so the emissions must be reconstructed using available statistics.

Recently an attempt has been made to systematize the estimation of current emissions (OECD 1995a,b). Most of the research in the emission estimation field is concentrated in the estimation of current emissions. This is understandable, because in order to be able to effectively manage greenhouse gas emissions their current magnitudes must first be known. Most countries, Finland (Finland 1995) among them, have agreed under the Framework Convention on Climate Change (FCCC) to provide such estimates. In the cases examined here CO_2 clearly causes the greatest greenhouse impacts now and probably also in the future (e.g. [IV] and [VII]): fortunately the emissions of CO_2 are also known most accurately.

When estimating the radiative forcing impact of Finnish (or other national) emissions, it is not sufficient to inspect just the current level of the emissions. For a more complete view the emissions of the past must also be included, because their effects linger for a long time after the actual emissions. In practice the choice of the methodology used to estimate the past emissions is mainly governed by the amount and type of relevant statistics found from literature. Because one aim of this work is to take a look at the likely future impacts of Finnish (and Nordic) emissions, scenarios for the future must also be

defined. In the following the discussion concentrates on the estimation of emissions of Nordic countries (including Finland).

2.2.1 Estimation of CO_2 emissions

Fossil CO_2 emissions are caused by energy production and are quite accurately known. CO_2 emissions from energy production can be estimated accurately from fuel consumption using fuel-specific emission coefficients, because most (typically approx. 99 %) of the carbon in the fuels is oxidized during the combustion process (e.g. Boström 1994) and the carbon content of fuels is generally well known (e.g. OECD 1995b). Historical statistics on fuel consumption (given either as amount of fuels spent e.g. tons of coal or as primary energy content) are available for several decades both for Finland [I] and other Nordic countries [VII]. Import, export and production data can be used to estimate the fuel consumption from the 19th century [VII]. For recent decades the uncertainty of the CO_2 emissions on a national level, caused mainly by inaccurately known fuel consumption data, is approximately ± 5 % (OECD 1995a). The estimates for earlier years are less accurate.

The carbon sink of the Finnish forests is estimated based on estimates of the stemwood volume, average carbon content of dry wood, average density of dry wood and the amount of branches, foliage and roots relative to the stemwood volume [II]. The stemwood volume has been periodically measured starting from the 1920's.

When comparing different energy production alternatives [V] the CO_2 emissions from combustion are accurately known (see above). In addition to this the indirect CO_2 emissions (e.g. emissions from the operations producing the fuel) are estimated. The carbon sink of renewable fuels (trees, peat) is also taken into account.

2.2.2 Estimation of CH_4 emissions

At the moment waste management (municipal and industrial waste waters; landfills), agriculture and energy production are the main anthropogenic sources of methane in both Finland and all other Nordic countries [VII]. Uncertainties in individual emission categories are large, and the total uncertainty in the current Finnish methane emissions on the national level is on the order of ± 40 % [VI] for recent years and even larger before that.

Methane emissions due to agriculture in the past have been estimated [IV, VI, VII] based on the number of livestock found from national statistics and using emission coefficients found in literature (e.g. Bingemer and Crutzen 1987; van Amstel 1993). Statistics on the number of livestock can be found starting from at least the 19th century [VII].

The estimation of emissions from wastes is more problematic. Statistical data on waste production - and treatment - exist only for recent years, and it is even then mainly based on quite crude estimates. Furthermore the emission coefficients relating waste production to actual emissions are quite uncertain, e.g. due to lack of reliable data [VI]. Past CH_4 emissions due to waste have been assumed to be directly proportional to GNP (Gross National Product) and population ([IV]; municipal wastewater in [VI]), population itself [VII] and even gross value of industrial production (industrial waste waters in [VI]). For emissions from landfills a first-order differential equation is used in [VI], with waste generation proportional to population and GNP. Methane emissions from energy production are mainly caused by small-scale combustion and indirect emissions from oil and natural gas production [IV,VI,VII].

In the comparison of different energy production methods the methane emissions from peatlands have been assumed to be national average, and cease after draining [V].

2.2.3 Estimation of N_2O emissions

At the moment nitrous oxide emissions in Finland and Nordic countries in general are mainly caused by agriculture, industry, energy production and nitrogen deposition [VI] [VII]. As with CH_4, uncertainties within individual emission categories are large, and the uncertainty of current Finnish emissions is somewhat below ± 40 % [VI], and the uncertainty increases with distance in time.

N_2O emissions from cultivated land have been estimated based on the land type and area [IV,VI], and from fertilization (commercial fertilizers and manure use) assuming that approximately 1 % of N is converted into N_2O [IV,VI,VII]. Industrial emissions in the past have been assumed to be proportional to GNP, with current estimates calculated with production or use volumes and emission factors [VI] or taken from national reports [VII]. Emissions from energy production are calculated using fuel and combustion method specific emission factors, and data on fuel usage [IV, VI, VII].

2.2.4 Emission estimation of CFCs and substitutes

Emissions of CFCs and substitutes (mainly HCFCs and HFCs) are calculated for Finland from import data, taking into account product-specific delays in the release of the gases after consumption [III].

2.2.5 Future scenarios of emissions

In the study of climate change future emissions are often described by several scenarios that are hoped to cover the range of possible actual values (e.g. IPCC 1990; 1992; Enting et al. 1994). This is due to the fact that it is notoriously hard to predict what will actually happen in the future (MacKellar et al. 1995: United Nations 1992). Instead of attempting to pin down the most probable outcomes, in this thesis simple Finnish scenarios have been chosen that are expected to capture much of the range of possible emissions developments.

For Finnish fossil CO_2 emissions four different emission scenarios (F_A, F_B, F_C, F_P) have been defined [I], one of which (F_P) is used only in [I] and the others in [I, II, IV]. The upper range of emissions is assumed to be captured by F_A, where emissions will continue to increase until the year 2100. The lower bound is defined by F_C, where the emissions will be 25 % below the 1990 value in 2025, and decrease by 3 % (approximate rate for infrastructure renewal) annually thereafter. For carbon storage in forests three different paths have been defined (B_1, B_2 and B_4) that result in doubling of the 1990 standing stock of forest biomass [II]. In B_3 growth of carbon storage in forests is assumed to stop in the beginning of next century. Hypothethised net carbon loss of forests has not been considered in the scenarios.

Three future scenarios were originally defined for CH_4 and N_2O [IV]: one (M_A and N_A) with 50 % increase, another (M_C and N_C) with 50 % decrease and the middle (M_B, N_B) one with no change from 1990 emissions. Later [VI] the short term changes were made more realistic and only a base case and a reduction scenario were defined. Furthermore no change in the emission levels was assumed to take place after 2010.

For Nordic emissions [VIII] high (A) and low (B) emission scenario have been devised. It has been assumed that there are two independently working "forces", where one is the current estimated linear trend, and another is an exponentially (parameter α) decreasing emission path. The actual emission scenarios are formed as a linear combination of these two trends by assuming a time dependent exponential change (parameter β) in the weights. The scenarios A and B differ in the values assumed for α and β (1%/a for A and 3%/a for B).

The future emissions of CFCs and HCFCs are assumed to comply with the Montreal Protocol and its amendments, and the use of substitutes (represented by HFC-134a) is assumed to reach double the current volume [III].

2.3 Uncertainty of results

the results of the radiative forcing calculations are often used in comparisons, instead of using just the absolute values. Two most typical cases are inter-scenario comparisons, and intertemporal comparisons. In the former the radiative forcings caused by two emission developments (scenarios) are compared at some specific time, e.g. year 2100 ("which scenario has smaller impact, and by how much?"). In the latter case the radiative forcings caused by one emission scenario at two time points are compared with each other, e.g. radiative forcing at 2100 compared to "current" radiative forcing ("at how much higher level will we be by the year 2100?". In such cases the error sources of the estimates correlate, *decreasing* the uncertainty of the results below the uncertainty level of the absolute radiative forcing estimates.

In absence of the correlation mentioned above, assuming normal distributions, the total uncertainty of the results could be approximated with an emission-strength based norm of the individual uncertainties. With the correlations this approach will overestimate the actual uncertainty, however.

The impact of the correlations on the final uncertainty of the results is demonstrated in the following manner for two specific cases. First, the estimated Finnish radiative forcings at different time points are compared with each other, and then the estimated Finnish radiative forcings are compared with Nordic estimates for the same time point.

2.3.1 Comparison between two points of time

The emission estimates for the year 1990 are assumed to be lognormally distributed and to contain a gas-specific uncertainty U_E (± 40 % for the emissions of CH_4 and N_2O, and ± 10 % for emissions of CO_2). Thus in the simulations a realization of the emissions $E_{g,1990}$ for year 1990 for gas g are given by

$$E_{g,1990} = E_{b,g,1990} * \exp(rnd1)$$
$$rnd1 = N(0, \delta_{Ue}), \qquad (4)$$

where N(μ,σ) denotes a normally distributed random number, and the standard deviation σ_{Ue} is calculated based on the uncertainty U_E (defined above) assuming that the range represents the 80% confidence interval of a normally distributed variable, and the gas-specific base scenario emissions are denoted by $E_{b,g,1990}$.

The emissions are assumed to be lognormally distributed, because otherwise the realization of the emissions in a simulation might be too close to zero. The lognormal distribution also reflects my opinion that the uncertainty ranges of emission estimates are not symmetrical (when uncertainty is given as ± x% I feel that it is more likely that the actual figure is +x% than -x% off the specified value. This distinction become more pronounced when dealing with relatively large announced uncertainties, as is the case with CH_4 and N_2O emissions.

Past and future (relative to 1990) emissions are assumed to contain an additional uncertainty U_{Et} that is assumed to be proportional to the basic emission uncertainty U_E and to the square of the distance in time. Thus the simulated emissions of year t for gas g are expressed by

$$E_{g,t} = E_{b,g,t} * \exp(rnd1 + N(0, \delta_{Ute}))$$
$$\delta_{Ute} = a\delta_{Ue}\left(\frac{t-1990}{200}\right)^2, \qquad (5)$$

where rnd1 is the same random number generated for the 1990 values (eq. 4) and σ_{Ute} is the additional uncertainty due to time. In the simulations a = 1.

After the determination of the emission profiles E(t) according to equations (4) and (5) for the gases, the concentration changes in the atmosphere C(t) are

calculated. For CH_4 and N_2O a realization of the lifetime α used in the concentration calculations is

$$\begin{aligned} \alpha &= \alpha_b rnd2_a \\ rnd2_a &= N(1, \delta_g), \end{aligned} \tag{6}$$

where α_b denotes the original (base) atmospheric adjustment time (eq. 1), and σ_g is determined from the gas-specific uncertainty range (± 25 % for each gas), assuming that the variable is normally distributed and that the range represents the 80 % confidence interval.

For CO_2 the uncertainty of the concentration calculations is simulated by modifying the pulse response coefficients of equation (3) used in the calculations. A random number $rnd2_b$ generated from a distribution of N(1, σ_g) is used to either increase ($rnd2_b < 1$) the coefficients of short time constants and decrease the coefficients of long time constants or vice versa ($rnd2_b > 1$), keeping the sum of the constants at unity. The amount of increase/decrease depends on how much $rnd2_b$ deviates from unity. For example for $rnd2_b = 0.7$ the pulse function (3) becomes

$$f(t) = 0.0 + 0.032e^{-t/362.9} + 0.321e^{-t/73.6} + 0.249e^{-t/17.3} + 0.398e^{-t/1.9}, \tag{7}$$

increasing the removal rate of CO_2 by approximately 30 %. The accuracy of carbon cycle models used as the basis of this work (1.2.2) is on the order of ± 20 % (IPCC 1996), which is used to determine σ_{CO_2}.

The uncertainty of the radiative forcing calculations is simulated by multiplying the original gas-specific radiative forcing function $RF_b(C)$ by a random number

$$RF_g(C) = RF_{b,g}(C)rnd3$$
$$rnd3 = N(1, \delta_g), \tag{8}$$

where σ_g is determined from the gas-specific uncertainty range (± 20 % for each gas), assuming that the variable is normally distributed and that the range represents the 80 % confidence interval.

The simulation described above is performed 2000 times, and the total radiative forcing results

$$RF_i(t) = RF_{i,CO_2}(t) + RF_{i,CH_4}(t) + RF_{i,N_2O}(t), i = 1...2000 \tag{9}$$

are divided into 10 groups G of 200 runs each (groups of 200 simulation runs are used because 200 runs is a sufficient amount to estimate the standard deviation from; Efron and Tibshirani 1993). For each simulation the ratios

$$dRF_{G,i,c}(t) = \frac{RF_{G*200+i}(t)}{RF_{G*200+i}(1990)}, \quad i = 1...200, G = 0...9$$
$$dRF_{G,i,n}(t) = \frac{RF_{G*200+i}(t)}{RF_{G*200+i+1}(1990)}, \quad i = 1...199, G = 0...9 \tag{10}$$

are calculated, where $dRF_{G,i,c}(t)$ represent the actual situation where the uncertainties correlate and $dRF_{G,i,n}(t)$ represent a situation where no correlation is assumed to exist between the causes of uncertainty for the estimated Finnish radiative forcings at different points of time. The total uncertainty of the resulting radiative forcings is represented by the ratio

$$R_{G,x}(t) = \frac{stdev(dRF_{G,i,x}(t))}{average(dRF_{G,i,x}(t))}, \quad x = c,n;\ G = 0...9\,. \tag{11}$$

It is instructive to compare the resulting ratios $R_{g,n}$ and $R_{g,c}$ with

$$R_G(t) = \frac{stdev(RF_G(t))}{average(RF_G(t))}, \quad G = 0...9\,, \tag{12}$$

that represents the spread of the absolute results in the simulations.

2.3.2 Comparison between two emission scenarios

The uncertainty of the ratio of the Finnish and Nordic radiative forcings is simulated in a manner similar to section 2.3.1. The first 1000 simulations of the Finnish radiative forcings $RF_i(t)$ (9) are compared with 1000 simulations of Nordic radiative forcings $RF_{N,i}(t)$ that have been calculated in the manner described by equations (4) - (9), but with Nordic emission scenarios. Perfect correlation of causes of uncertainty is assumed to exist in the calculations of the concentration changes (6) (7) and radiative forcing (8) (i.e. in the calculations of $RF_{N,i}(t)$ and $RF_i(t)$ the same random numbers ($rnd2_a$, $rnd2_b$ and rnd3) are used) because the two emission scenarios produce emissions to the same atmosphere, and thus the removal rates and caused radiative forcings must be the same. The uncertainties of the 1990 emission estimates are assumed to correlate strongly (correlation 0.9), and thus eq. (4) becomes

$$\begin{aligned} E_{g,1990} &= E_{b,g,1990} * \exp(rnd4) \\ rnd4 &= N(0,\delta_{Ue}) \,|\, corr(rnd4, rnd1) = 0.9, \end{aligned} \tag{13}$$

where rnd1 has been determined in eq. (4). As in the Finnish case, the 1000 simulation runs are divided into 5 groups of 200 runs, for which the ratio of Finnish to Nordic radiative forcings

$$dRF2_{G,i,c}(t) = \frac{RF_{F,G*200+i}(t)}{RF_{N,G*200+i}(1990)}, \quad i = 1...200, G = 0...4$$
$$dRF2_{G,i,n}(t) = \frac{RF_{F,G*200+i}(t)}{RF_{N,G*200+i+1}(1990)}, \quad i = 1...199, G = 0...4 \tag{14}$$

are computed (index F denotes Finnish and N Nordic radiative forcings), where $dRF2_{G,i,c}(t)$ represents the actual situation where the causes of the uncertainties correlate and $dRF2_{G,i,n}(t)$ represents a situation where no correlation is assumed to exists between the causes of uncertainty for the estimated radiative forcings of Finland and Nordic countries. From the relative values (14) the ratio

$$R2_{G,x}(t) = \frac{stdev(dRF2_{G,x}(t))}{average(dRF2_{G,x}(t))}, x = c, n, G = 0...4. \tag{15}$$

is calculated.

As in section 2.3.1,it is instructive to compare the resulting ratios $R2_{g,c}$ and $R2_{g,n}$ with

$$R2_G(t) = \frac{stdev(RF_G(t))}{average(RF_G(t))}, \quad G = 0...4, \tag{16}$$

that represents the spread of the absolute Nordic forcing results in the simulations.

3. Results

3.1 Greenhouse impacts of continuous regional emissions

This part of the thesis relies on the articles [I-VIII]: the comments about the applicability and uncertainty of the results presented in them and elsewhere in this thesis should be kept in mind. The conclusions especially about the state of future forcings depend heavily on the emission scenarios used in the articles.

According to the calculations the Finnish contribution to the current (1990) global average direct radiative forcing is somewhat higher than the proportion of population ((3.8 mWm^{-2} equals 1.5 per mill of the estimated current global radiative forcing, while 5 million inhabitants equals roughly 1 per mill of the global population). On the other hand the shares of individual gases range from approximately 1.3 per mill (CO_2 and CH_4) to 1 % (N_2O).

The Finnish fossil CO_2 emissions have increased rapidly between the 1950's and the 1980's, after which the rate of increase has decreased somewhat [I]. According to calculations even relatively rapid reduction of CO_2 emissions will not succeed in reducing the radiative forcing caused by the emissions. On the contrary, even the lowest emission scenario results in increasing radiative forcing until the middle of the 21st century, after which the greenhouse impact will slowly decrease. Because the removal of atmospheric CO_2 is slow, even by the year 2100 the past (pre-1990) emissions will cause half of the forcing they cause in 1990 [I, fig 3].

In [II] the carbon sink of Finnish forests between the 1920's and 1990 are calculated to reduce the 1990 radiative forcing caused by fossil CO_2 emissions by almost 50 %. Unless fossil CO_2 emissions continue to increase, the forest management practices will play a significant role in the reduction of Finland's contribution to global radiative forcing. If fossil CO_2 emissions increase as is

assumed in scenario F_A, the development of forest carbon sink will not significantly change the calculated radiative forcings.

The Finnish emissions of CFCs and HCFCs have increased rapidly in the past [III], but due to Montreal Protocol and its amendments their emissions are estimated to also decrease quickly in Finland; also the emissions of HCFCs will be limited [III]. CFC-12 causes the largest greenhouse impact (direct radiative forcing) of the CFCs and related compounds in Finland. Altogether approximately 15% of the current radiative forcing caused by Finnish emissions is caused by CFCs and related compounds. Even though the Finnish emissions of CFCs are assumed to cease before the year 2000, they will cause approximately half of the total direct radiative forcing of CFCs and related compounds [III] even in the year 2100 (and approximately 30 % of the projected maximum forcing of 0.6 mWm^{-2} that is estimated to take place early next century). In the scenarios considered CFCs are also the greatest Finnish source of stratospheric chlorine molecules (that are connected with ozone loss) up to the year 2100 [III].

According to [IV] the Finnish CH_4 emission in the past have remained practically constant during the last 50 years, before which they doubled from the level of the year 1900. N_2O emissions increased slowly from the 1900's until the 1950's, and rapidly thereafter due to new growing emission source categories (fertilizers, industry, energy). Until the middle of this century methane was the main Finnish cause of radiative forcing, but since then CO_2 has been the dominant greenhouse gas, and will remain so in the future. At the moment the fossil CO_2 emissions account for over 50 % of the Finnish radiative forcing, and even assuming increasing CH_4 and N_2O emissions (M_A and N_A) and decreasing (F_C) fossil CO_2 emissions still over 50 % in the year 2100. At the moment both Finnish CH_4 and N_2O cause approximately equal amounts of radiative forcing. The impact of N_2O is increasing continuously both in

absolute value and relative to CH_4 and is likely to be over twice that of CH_4 in the year 2100.

CO_2 is the dominant greenhouse gas when comparing the radiative forcings caused by different energy production schemes [V] (Savolainen et al. 1994). When comparisons are made assuming continuous production of energy, peat from natural peatlands is comparable to coal in terms of radiative forcing caused according to the calculations, due to very slow renewal of the peat carbon store of the peat fuel production area. Wood from planted stands and forest residues have clearly the smallest greenhouse impact out of the choices studied. Peat from cultivated peatlands and merchantable wood are comparable to coal in the short (< 50a) term, to natural gas in the medium (50 a - 100 a) term and cause less greenhouse impact than any fossil fuel in the long term (300 a). The results obtained in [V] are relatively insensitive to the assumptions made, with the exception of merchantable wood, where the different choice of initial state of the forest and reference case may increase the caused forcing considerably.

In [VI] Finnish CH_4 and N_2O emission scenarios and estimates for 1990 are refined from those used in [IV]. They still agree reasonably well with the previous estimates, the largest difference being that the N_2O emissions are estimated to have increased more steadily in the past. In the base scenario the CH_4 emissions remain approximately at current level, and in a reduction scenario decrease by about 50 %. N_2O emissions increase in the base scenario by 50 % in the near future (by 2010), and decrease by some 10 % in the reduction scenario. No changes in the emissions are assumed after 2010. The CH_4 and N_2O emission estimate result in approximately equal radiative forcings up to 1950's, but since then the impact of N_2O has been increasing rapidly (doubling from the 1950 value by 1990), whereas the impact of CH_4 emissions has remained steady. The reduction scenario rapidly (within 20 years) decreases the impact of CH_4 emissions by almost 50 %, while the radiative forcing caused by N_2O emissions will continue to increase until the end of calculation period

(by 50 % in the reduction case and by 150 % in the base case). Despite the increasing impact of N_2O, CO_2 will remain the dominant gas in the future, causing approximately 75 % of the total radiative forcing in 2100, assuming emission reduction scenario F_B ([I]).

In [VII] the methodology used in [I], [IV] and [VI] is applied to the Nordic countries. According to the estimates the emissions in all the Nordic countries have followed similar patterns to those found in Finland with some exceptions. Generally both CO_2 and N_2O emissions have increased strongly, while CH_4 emissions have remained relatively steady. On the other hand the Swedish CO_2 emissions have decreased noticeably since the 1970's and the Norwegian CO_2 emissions have not increased as much as in the other countries. The total radiative forcings due to anthropogenic fossil CO_2, CH_4 and N_2O emissions in the Nordic countries have increased by at least a factor of 6 (from 1900 to 1990). At the same time the per capita radiative forcings have at least tripled for all the countries. Even by the year 2100 approximately 50 % of the radiative forcing caused by emissions emitted before 1990 still remain.

In the last article included in this thesis [VIII] two future scenarios are attached to the Nordic emission histories [VII]. If very strict emission reductions take place (scenario B), the Nordic radiative forcing would return to approximately current levels by the end of the next century. The higher emission scenario results in doubling of the current radiative forcing. When radiative forcing per capita is considered as an equity criteria, and the global radiative forcings per capita resulting from some stabilization levels and population growth assumptions are calculated, it is apparent that if the Nordic emissions follow close to the higher emission path (scenario A) the Nordic per capita forcing will remain above all included global measures. If Nordic emissions are reduced strongly (scenario B) it is possible to achieve global per capita forcing by the end of the next century, provided that current population numbers are used for

the calculation. If projected year 2100 population is used, both scenario A and B result in above global average per capita radiative forcing.

3.2 Uncertainty of the results

Several different causes of error exist in the results presented above. Some emission sources that should be taken into account as anthropogenic, e.g. draining of peatlands in Finland - this has been examined in Laine et al. (1996b) - have not been included. Others have been included incompletely (e.g. the forest sink has been taken into account only either from the 1920's [II] or not at all in the Nordic studies [VII - VIII]). On the other hand it is argued that the N_2O emissions from agricultural fields [IV, VI] should not be counted as anthropogenic (OECD 1995b). The error introduced by these "inclusion problems" is hard to quantify.

The impact of uncertainties in emission estimates and radiative forcing modeling (concentration and radiative forcing calculations) on the results can be evaluated, however. The uncertainty of the absolute radiative forcings is quite high (the actual magnitude depends on the relative strengths of the sources of the different greenhouse gases). For CH_4 and N_2O the greatest single uncertainty source is the inaccurately known emission strengths (± 40 % or even more), whereas for fossil CO_2 the accuracies of the radiative forcing and concentration calculations (± 20 % each) are typically the determining factor. On the other hand the uncertainty of emissions may also be more significant for CO_2 in cases related to biospheric sinks and emissions (e.g. Minkkinen and Laine 1996).

If the sources of uncertainty are assumed to be independent, the total uncertainty of the calculations is of the order of ± 40 % for current emission strengths [VI]. In practice the absolute figures are rarely interesting when the impacts of non-global emissions are examined. This is due to the usage of the results, which typically is aimed at some sort of comparisons. Therefore the uncertainty of

some *relative* results is more interesting. Then the sources of uncertainty tend to have a positive correlation, which increases the accuracy of the relative results.

As a demonstration of the significance of the correlation on the relative results between two time points, the values obtained for $R_{G,X}$ (t) (eq. 11), the ratio of standard deviation to the mean value of the simulated change in radiative forcing between year t and year 1990 for a Finnish greenhouse gas emission scenario F_B, M_B, N_B [IV], are shown in Fig. 2 for 10 groups of simulations (of 200 runs each) as a function of time. For reference purposes similar ratios are shown also for the absolute results (B).

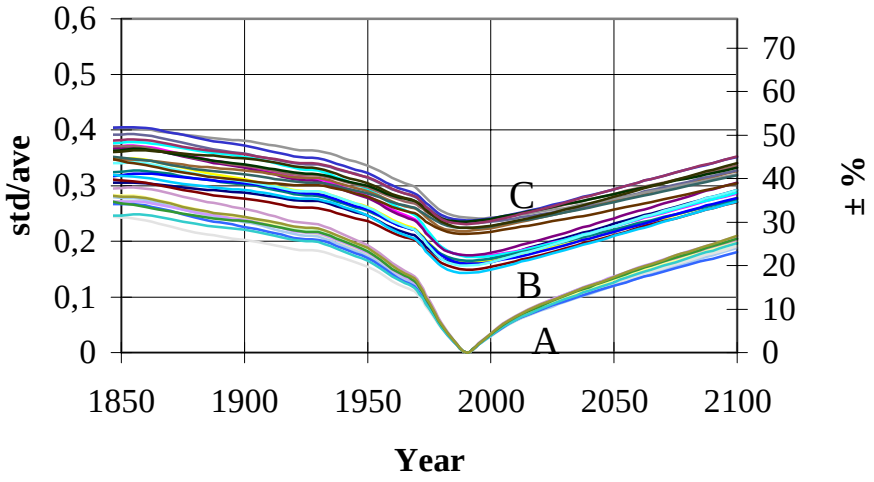

Fig. 2. Simulated uncertainty of absolute and relative radiative forcing results, given as the ratio of standard deviation and average (std/ave) for 10 groups of 200 simulation runs each. For relative results the value of Finnish radiative forcing at year t has been divided by the value for 1990. The lowest curve group (A) corresponds to the case where correlations are assumed to exist across time between the sources of uncertainty (emission estimation, concentration calculations, radiative forcing calculations), the middle group (B) represents the uncertainty of the absolute radiative forcing calculations, and the highest group of curves (C) is due to assuming no correlation between causes of uncertainty. See text for simulation details.

From the results presented in Fig. 2 it appears that the use of relative measure improves the confidence of the results considerably in the future and near past (A vs. B). If there was no correlation between the uncertainties, the use of relative measure would somewhat increase the uncertainty (C vs. B). This latter phenomenon is a direct consequence of the fact that the division of two random uncorrelated variables increases the variance.

As a demonstration of the significance of the correlation on the relative results between two emission scenarios, the values obtained for $R2_{G,X}(t)$ (eq. 15), the ratio of standard deviation to the mean value of the simulated change in radiative forcing between year t and year 1990 for a Finnish greenhouse gas emission scenario (as in Fig. 2) and a Nordic emission scenario where CO_2 emissions will increase during the first quarter of the 21st century and decrease thereafter, and N_2O and CH_4 emissions will decrease ([VIII], scenario A), are shown in Fig. 3 for 5 groups of the two cases (A, C) as a function of time. In A correlation is assumed to exist between the sources of uncertainty, while in C no correlation is assumed. For reference the same ratio (eq. 16) is also shown for the absolute Nordic radiative forcings.

As in Fig. 2, the existence of the correlations greatly reduces the uncertainty of the results. According to the simulations the uncertainty of the relative results remains quite good (curve group A). This is due to the fact that in the scenario used in the simulations CO_2, whose emissions are most accurately known of the three greenhouse gases considered in this simulation, contributes over 60% of the total radiative forcing in the future (the uncertainty of the concentration calculations and the radiative forcing calculations plays no role here, since they are assumed to be perfectly correlated between the compared cases).

In the examples presented above, the use of relative measures of greenhouse impact reduces the uncertainty, especially when used in the estimation of future

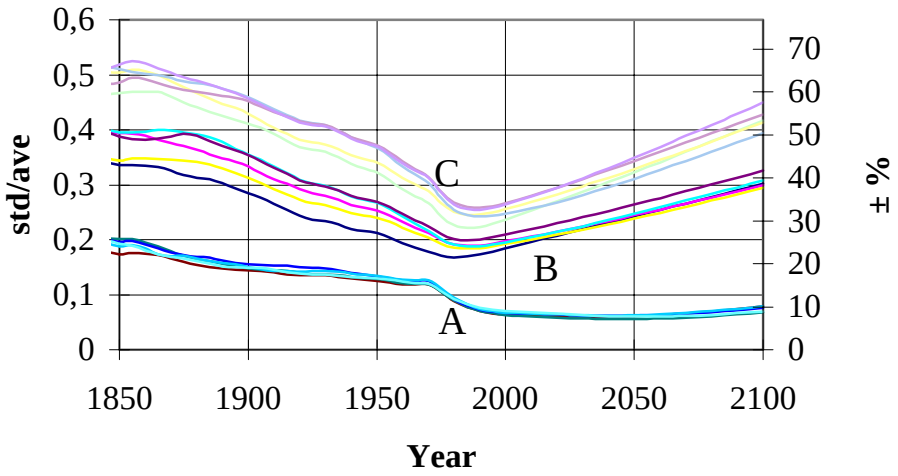

Fig. 3. Simulated uncertainty of absolute and relative radiative forcing results, given as the ratio of standard deviation and average (std/ave) for 10 groups of 200 simulation runs each. For relative results the simulated value of Finnish radiative forcing at year t has been divided by the simulated value of Nordic radiative forcing for year t. The simulated Nordic radiative forcings have been used for the absolute curves (B). The lowest curve group (A) corresponds to the case where correlations are assumed to exist across time between the sources of uncertaint, the middle group represents the uncertainty of the absolute radiative forcing calculations (B), and the highest group of curves is due to assuming no correlation between causes of uncertainty (C). See text for simulation details.

impacts. This is partly due to the similarity of greenhouse gas emission scenarios in the cases used in the comparisons. In comparisons between two cases where for example CO_2 emissions would dominate one and CH_4 emissions the other case in terms of caused radiative forcing (e.g. treatment of organic wastes, where combustion produces mainly CO_2, and storage in landfills produces mainly CH_4) the correlations between the sources of uncertainty would not improve the final uncertainty. These kind of situations are rare in practice, however.

4. Discussion

Radiative forcing allows us to examine different greenhouse gases on the basis of a common quantity. The required calculations are computationally simple and they can be easily performed for arbitrary greenhouse gas emission and sink profiles. It is suitable only for greenhouse agents that can be assumed to be uniformly mixed in the atmosphere: this excludes e.g. tropospheric ozone and aerosols (e.g. Kulmala et al. 1995). Increasing levels of aerosols have an opposing (cooling) effect. Locally the radiative forcing balance may be even negative (suggesting net cooling). This counterbalance will soon be overshadowed by the rapidly increasing radiative forcing, because aerosol levels follow very rapidly changes in the emissions, whereas greenhouse gases accumulate into the atmosphere over time. In Savolainen et al. (1997) the inclusion of aerosols when assessing the greenhouse impact of different fuels in energy production has been crudely examined.

Similar method of radiative forcing calculations used in this thesis have been applied to the study of global impacts by others. MAGICC model (Hulme et al. 1994) has in fact been used extensively in the estimation of the impacts of the (global) IPCC scenarios (IPCC 1990; 1996), including estimating the global warming and sea level rise with simple differential equations. In my opinion the main value of this thesis lies in the estimation of the past emissions for Finland and Nordic countries, and in the application of the radiative forcing calculations to regional scale emissions. To my knowledge no similar work has been published, with the exception of [V]. Similar approaches to [V] have been used by Zetterberg (1993), Hillebrand (1993), Rodhe and Svensson (1995) and Zetterberg and Klemedtsson (1996). In the last work the authors reach a different conclusion from [V]; this is apparently mainly due to a very generously chosen CO_2 emission coefficient for peat by Zetterberg and Klemedtsson.

On hindsight it would probably have been more convenient to choose some increasing global concentration scenario (e.g. some moderate IS92 scenario (IPCC 1992)). On the other hand, the inclusion of the effect of increasing global concentrations would result in the discounting of the forcing impacts of the future Finnish emissions, which is not necessarily desirable.

In [V] a "bubble" is formed over the land area that is used for energy production, and greenhouse gas flows through the bubble surface are examined, and their greenhouse impact over time calculated. Another approach would have been to form such a bubble over the total land area suitable for such purpose. Probably some land area would have to be excluded from the latter type of examination on the basis of its practical unavailability for energy production purposes, but nevertheless I feel that the latter method would undoubtedly produce more favorable results as far as the greenhouse impact of energy use of wood and peat is considered, since with the scheme used in [V] the slow regeneration of biomass severely penalizes them in the short-term.

In the publications included in this thesis the emissions have been predefined, and radiative forcing has been used to examine the impacts of the scenarios. By intelligent construction of the scenarios some relevant conclusions may be drawn with even such a simple approach. The Finnish emission scenarios have been originally devised in the early 1990s, and at least for the time being they are not far off the actual development of emissions (Finland 1995). The REFUGE-model has also been used to examine the effect of the possible drying of Finnish peatlands (Laine et al. 1996a), to estimate the impact of mire drainage for forestry (Laine et al. 1994), and to calculate the impact of the Finnish peatlands on the radiative forcing during 1900 - 2100 (Laine et al. 1996b). Sinisalo and Savolainen (1996) combine the two latter results with the Finnish anthropogenic emission scenario results presented in this thesis.

In theory radiative forcing calculations accompanied with estimates or models on the costs of greenhouse gas emission reductions could be used to design cost-effective greenhouse gas emission reduction strategies (e.g. some target radiative forcing development could be defined, and the cheapest way to reach it could then be calculated). Some theoretical attempts towards this direction have been taken (e.g. Tahvonen 1994), but the feedbacks between climate change and economy make the cost estimation difficult.

The advantage of radiative forcing calculations over the other method of non-global emission impact assessment, the use of global warming potentials (GWPs), is that it explicitly takes into account the atmospheric lifetimes of the greenhouse gases in the results and thus displays some of the inertial features of the problem. This is essential when the emissions are not constant and the results are used to evaluate the difficulty and/or possibilities of greenhouse impact reductions. On the other hand the meaningful application of radiative forcing calculations requires that the emissions are given as a function of time. Emission figures should also be available for a longer time period than that of interest: otherwise the results in the beginning of the time period will be dominated with ”cold-start” effects.

A problem with the presentation of the results as radiative forcings is that the comparison of radiative forcing developments is not always simple, because the impacts vary with time. Thus it is possible that one option is better in the beginning and the other in the end of the time interval under study. One way to solve this problem is to simply integrate the impacts over time, and study the total impacts. This approach implicitly assumes that damage in the near and far future are as harmful, but no better, generally accepted solution has been found for this problem so far.

Greenhouse impact estimation is full of uncertainties at all levels. Furthermore it appears that significant improvements in the precision of the predictions are

not to be expected soon (Morgan and Keith 1995). In this work radiative forcing is used as an indication of the actual climatic change. Because the objective is to study the impact of local emissions, the inclusion of some kind of relationships between global warming or climatic change and radiative forcing would serve only to make the final results less reliable.

On the chain from emission estimation to radiative forcing calculation the largest uncertainties are typically caused by the emission estimation (for the past) and scenario development (the future scenarios suffer naturally from the same uncertainties as the current emission estimates). In many cases the estimates of past emissions presented in this thesis should be regarded as first approximations, which hopefully will serve as starting points for later attempts. Furthermore, in my opinion the CH_4 and N_2O scenarios should have been defined more carefully, but useful insights may be gained from even these simple assumptions. Even the estimates of current emissions contain quite large uncertainties, and projections into the future present additional difficulties. Fortunately the uncertainty of the results can usually be reduced considerably by examining impacts on a relative scale, i.e. comparing impacts of alternative emission scenarios or between two points in time. This approach should be used whenever practical.

Even though the term global warming is generally used instead of climate change, it must be noted that it is not accurately known what the actual effects of the concentration increases of greenhouse gases will be. Since not all negative and positive feedbacks of the global climate system are well known, it is possible - although not probable - that actual global warming will be minor. Especially the role of clouds is still quite uncertain. However, ”any change in the radiative balance of the Earth will tend to alter atmospheric and oceanic temperatures and the associated circulation and weather patterns. These will be accompanied by changes in the hydrological cycle (e.g. altered cloud

distributions or changes in rainfall and evaporation regimes)" (IPCC 1996). Even with minor global warming the impacts on society may be huge.

When radiative forcing - or global warming potential - calculations are used to assess the impact of the emissions, it is important to bear in mind the complex and non-linear relationship between radiative forcing and its actual effects on climate. The responses of e.g. vegetation to the changing climate are also likely to be non-linear. For example it has been postulated that the Gulf-stream may switch from one state to another due to global warming (Weaver et al. 1991). Any additional radiative forcing beyond such a point is irrelevant for Finland, although it may still cause some other effects. Thus, strictly speaking global average radiative forcing is only a continuous monotonous measure of the potential greenhouse impact of global emissions. However, when it is used in the comparison of different local emission scenarios, the non-linearities caused by the global aspect may be neglected.

5. Conclusions

Radiative forcing calculations are suitable for the estimation of the impacts of non-global greenhouse gas emissions. The most restricting limitations of this approach are that emissions must be given over the whole time period of interest, and that the interpretation of the results is not always easy (because the results are also given as a function of time, not as a single number).

The uncertainty of the absolute results is quite high (on the order of ± 40 %). For CH_4 and N_2O impacts the greatest uncertainty is due to uncertainties in emission estimation. For CO_2 the modeling of the atmospheric behavior of the gas is the weakest link. However, when the results are utilized in comparisons - either between scenarios or between time points - the uncertainty decreases noticeably. This latter approach should be used whenever practical when dealing with the results of the calculations.

According to the results both Finnish and Nordic greenhouse impact, measured as radiative forcing, has increased considerably during the 20th century, and will very probably continue to do so, unless very significant reductions in greenhouse gas emissions (especially CO_2) are achieved. This is mostly due to the long atmospheric lifetimes of N_2O and especially CO_2, and the probability that CO_2 emission will not be reduced significantly in the near future. The Nordic per capita radiative forcing is likely to remain above the global average, unless the current population levels are used as a basis for the calculations.

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