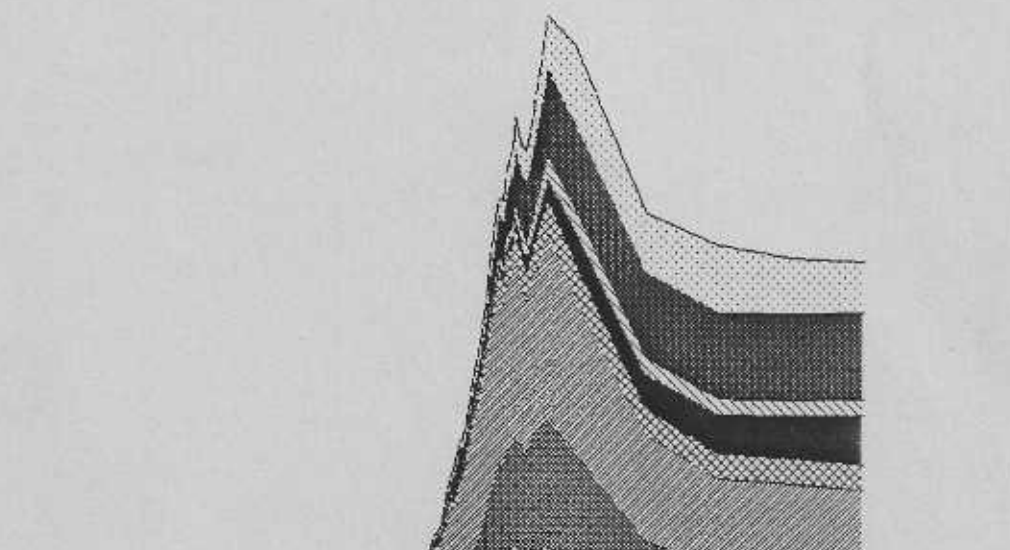
Historical and Future Regional Emission Paths of Carbon Dioxide :

Allocation and Optimization Mechanisms

Marco Janssen



Historical and Future Regional Emission Paths of Carbon Dioxide :

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by

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Contents

Preface

From june 1991 till january 1992 I was a trainee at the Centre for Mathematical Methods (CWM) of the Dutch National Institute of National Public Health and Environmental Protection (RIVM). This master thesis is the result of this period.

Global warming or the so-called greenhouse effect has been put forward as one of the most important environmental problems. International negotiations about response policies find itself to a problem of unusual complexity. To provide policy makers with a tool that gives a clear and concise overview of the workings of the greenhouse effect and the relevance of policy options, the RIVM initiated in 1986 the development of a computer simulation model of the greenhouse effect: IMAGE (an Integrated Model to Assess the Greenhouse Effect).
In this research IMAGE has been used for evaluating long-term climate strategies. This study consists of two parts. In part one the concept of emission debt is introduced, quantifying the fact that some regions have emitted more carbon dioxide in the past than were allowed on an equal share per capita. This instrument could be used as a starting point for tradable emission rights. In the second part an optimal allocation method is presented for calculating optimal regional carbon dioxide emission paths, based on minimization/maximization of specified socio-economic objective functions, like cost, under the condition that the induced climate change does not exceed sustainable climate targets.

Results of this study already entered the international area of negotiations. Estimates of emission debt have served as a basis for a background document for the presentation of the Dutch minister of Environment, J.G.M. Alders, at the UNCED meeting in Paris of the 2^{th} of December 1991. Results of emission debt are also used in December 1991 for the GLOBE-presentation *'The Environment in Europe: a Global Perspective'* in Brussels. An article about emission debt will appear in a special edition of the magazine *International Journal of Global Energy Issues*. An RIVM report of this study will be finished in the first half of this year.

I could never done this study without help of many other people at RIVM. I would express my deep gratitude to both Michel den Elzen and Jan Rotmans for their support and assistance during this research. Furthermore, I would like to thank Rob Swart and Bert de Vries for their valuable discussions. At the same time I would thank all other colleagues of the RIVM for the pleasant co-operation and support during my stay at the RIVM. I would also thank Nico Dellaert from the Erasmus University of Rotterdam for all his help.

Units

°C	degrees Celsius
ppmv	parts per million by volume
Gt	gigatons (10^{15} gram)
GtC	gigatons of carbon
tC	3.67 tCO_2
Wm^{-2}	watts per meter square
Mha	millions of hectares
bil	billion

Chemical Formulas

CFCs	chlorofluorocarbons
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
N_2O	nitrous oxide
NO_x	nitric oxides
O_3	ozone
OH	hydroxyl radicals

Regions

- EC (European Community (including former DDR)
- Rest of Western Europe (including Turkey)
- OECD East (Australia, New Zealand, Japan)
- Eastern Europe (excluding former DDR, including former Yugoslavia)
- former USSR
- North America (USA, Canada)
- Latin America (including Caribbean)
- Africa
- Middle East (including Israel, Iran, Afghanistan, excluding Turkey)
- Central Planned Asia (CPA) (China, North Korea, Vietnam, Kampuchea, Mongolia)
- South/Southeast Asia (excluding Japan)

* OECD (= EC, Rest Western Europe, OECD East, North America)
* Formally Central Planned regions (FCP) (= USSR and Eastern Europe)
* Developing regions (= Latin America, Africa, Middle East, CPA, SSEA)
* Developed/Industrialized regions (= OECD and FCP regions)
* Tropical regions (= Africa, Latin America, South/Southeast Asia)
* Boreal and Temperate regions(= Rest of the world excluding tropical regions)

1 Introduction

The possibility that increasing atmospheric concentrations of greenhouse gases may lead to significant climate changes faces the society with a problem of unusual complexity. International response is necessary to reduce the impacts of an enhanced greenhouse effect on society and natural ecosystems. Following the acceptance of the first scientific assessment of the Intergovernmental Panel on Climate Change (IPCC, 1990) by the Second World Climate Conference (WMO, 1991), the United Nations General Assembly commissioned an International Negotiations Committee (INC) to prepare an international agreement to respond to the anticipated enhanced greenhouse effect (UNGA, 1991).

International response is now considered appropriate by the majority of countries. Most of the OECD-countries have already announced or adopted policies to stabilize or reduce their emissions of carbon dioxide (most important greenhouse gas) as well as, in some cases, other greenhouse gases. However, lags in the global climate system (global warming which is still in the pipeline) and time-delays in adapting socio-economic and technological systems towards a global sustainable development (even in the case of maximum feasible effort), leading to inevitable future emissions, makes a certain amount of climate change in the future unavoidable. Therefore the response policies will have to be both adaptive and preventive in reducing the anticipated risks of climate change to accepted levels.

As a tool for developing policies which limit the effects of climate change, the Advisory Group on Greenhouse Gases (AGGG) identified several climate policy objectives (or targets) for climate policies, in order to protect the structure and functions of vulnerable ecosystems. Achieving these international targets requires the implementation of policies that will involve stabilizing or reducing emissions of greenhouse gases. This requires significant changes in industrial technology and may have profound economic impacts on modern societies which certainly affects the economy of a country.

This brings us to another important characteristic of such an effective international climate policy; how will the responsibility for future reductions in greenhouse gases be allocated among countries? The answer of that question could inevitably be related to the recognition of the present and historical inequities between developing and industrialized countries. This issue of north-south equity will certainly be addressed in the current negotiations about a common response to climate change. Developing countries should be enabled and supported to continue their development towards higher standards of living in a fashion that is consistent with the sustainability of the global biosphere. On the contrary, the industrialized countries are responsible for the major part of the present emission, and even more, for the accumulated historical emissions of greenhouse gases, released during the growth of these economies towards their present prosperity. Therefore based on equitable share of the global resources between the developed and developing countries, it is likely that the industrialized countries have already exceeded their equitable share, whereas the developing countries may still emit greenhouse gases based on this equity rule. In other words: the industrialized countries have built up a 'debt' with respect to greenhouse gas emissions, relative to the developing countries. In the first part of this study we discuss this concept of 'emission debt'.

Although the issue of equitable share of the global burden of controlling climate change is important in the present negotiations, it does not take the real regional costs and benefits

of emission control policies into account. In the second part part of this study an optimal allocation method is presented for allocating the emission reductions of carbon dioxide caused by fossil fuel combustion, based on minimization/maximization of a specified objective function, such as costs, under the constraint that the derived emission strategy does not exceed climate targets as defined by the AGGG. Since reliable assessments of costs and benefits of regional response policies, which are necessary to quantify the objective functions, are still not available, the method is used for rough estimates of those functions.
This study is build up as follows: In chapter 2 we first give a brief introduction to the climate change problem, as well as a description of the modelling tool we use to develop and evaluate long-term climate strategies: the Integrated Model to Assess the Greenhouse Effect (IMAGE) (Rotmans, 1990). Besides, we also discuss the emission scenarios developed by the International Panel on Climate Change IPCC (1991) and the sustainable targets of the AGGG (1990). In chapter 3 an estimatation of past CO_2 emissions is discussed as well as the concept of emission debt. In chapter 4 an optimization method is presented, which allocate regional CO_2 emission paths and several objective functions are discussed. The results of this optimization method, using several socio-economic objective functions, are presented in chapter 5. Results of this study are evaluated in chapter 6.

2 Climate Change and Sustainable Response Strategies

2.1 Climate Change

The Earth's surface temperature is determined by a natural greenhouse effect, caused by the trapping of long-wave terrestrial radiation emitted by the surface of the Earth in the atmosphere by mainly water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3). Without this balanced process the mean temperature of the Earth's surface would have been over about 30 °C lower. Within a relatively short time there is growing evidence that the past and continuing emissions from human activities are substantially increasing the atmospheric concentrations of greenhouse gases: carbon dioxide, methane, nitrous oxide, chlorofluorocarbons (CFCs) and other greenhouse gases, and induce an additional warming of the Earth's surface, the so-called global warming. Combustion of fossil energy, land use changes and in recent years the use of chlorofluorocarbons (CFCs) are the main activities responsible for the increase in the concentration of greenhouse gases. These increases lead to a net energy input to the lower atmosphere and result in an additional warming of the Earth's surface. So far the global mean surface temperature has increased by 0.3 to 0.6 °C over the last 100 years (IPCC, 1990), although because of natural variability and other factors we do not know how much the already emitted greenhouse gases contribute to this present observed temperature rise.
Results of simulation of ocean-atmosphere show an average surface temperature increase of 1.5 to 4.5 °C when CO_2 in atmosphere is doubled. A doubling of the CO_2 equivalent concentration[1] will appear before the middle of the next century when emissions remain uncontrolled.
The most important greenhouse gases are:
Carbon dioxide contributes to about 50% of the enhanced greenhouse warming and is currently rising at about 0.5% (1.8 ppmv) per year due to anthropogenic emissions. The main sources are the combustion of fossil energy and land use changes (primarily deforestation). The present world emissions of CO_2 due to fossil fuel combustion is 6 GtC in which Western- and Eastern Europe contribute respectively 15% and 24%. This source from the fossil fuel combustion is well known (± 5%), in contrast with the source from the land use changes, which is poorly known. At present the destruction of tropical forests releases about one to two GtC (FAO, 1991).
Methane is increasing at a rate of about 0.9% (0.015 ppmv) per year (although the rate of increase is declining) and contributes about 15% to current climate change. Major biogenic sources of methane are natural wetlands, rice paddies, landfills, domestic ruminants and biomass burning. Fossil sources are exploitation of coal and oil and natural gas venting and distribution. The oxidation of methane through hydroxyl radicals is the major sink mechanism, which atmospheric level due to increasing levels of other atmospheric pollutants is decreasing. Besides increasing methane emissions, the probably decreasing global hydroxyl availability, which removes methane from the atmosphere, leads to an enhanced level of methane in the atmosphere.
Nitrous oxide is increasing at a rate of 0.25% per year and contributes 6% to current greenhouse heating. The concentration of nitrous oxide is increasing at a rate of about

[1] The CO_2-equivalent concentration is defined as the concentration of CO_2 that by itself, would produce the same increase in direct radiative forcing as produced by all of the greenhouse gases under concern.

0.25% (0.8 ppbv) per year. The major sink of nitrous oxide is photochemical decomposition in the stratosphere. The observed increase in the atmospheric concentration of nitrous oxide concentration is assumed to be the result of anthropogenic influence on the nitrogen cycle. The most important sources of nitrous oxide are assumed to be soils, oceans, fertilizer use and forest to grassland/arable land conversion.
CFCs, HCFCs, HFCs and halons (halocarbons) are robust compounds which survive atmospheric 'clean up' processes and, after leakage into the lower atmosphere, diffuse up to the higher atmospheric levels. In the stratosphere the halocarbons are responsible for depletion of ozone; however, these chemicals play also a significant role in global warming, presently about 24%. CFC-concentrations increase with about 4% yearly. Recently emissions of halocarbons were regulated by London amendments of the Montreal Protocol, including a phase-out of all CFCs. There are no binding regulations for eventually phasing down the production of the alternative compounds.

Dependent on the assumptions and definitions it can generally be said that the agricultural (including deforestation) and industrial sector causes 35% of the problem, while 65% is caused by the energy sector (Okken *et al.*, 1989). Within the energy sector transportation, power generation and other combustion processes play about an equal role.
The carbonaceous fuels (about 80%) dominate the energy system of the world. Second important source is biomass (about 15%), although lack of data makes it difficult to quantify this contribution. The remaining 15% of the total 65% that the energy sector accounts for is caused by non-CO_2 emissions. As to methane four broad categories of fossil energy sources can be distinguished: methane release from coal mining; exploration and production of gas and oil; loss during transportation and distribution of natural gas; and combustion of fossil fuels (considered as only a minor source). Nitrous oxide is also emitted by combustion of fossil fuels. Carbon monoxide plays an essential role in the global CH_4-CO-OH cycle (Rotmans *et al.*, 1990). More than one-third of the carbon monoxide emissions is caused by fossil fuel combustion, primarily in the transportation sector. Nitrogen oxides and non-methane hydrocarbons are precursors to tropospheric ozone (O_3), which also acts as a greenhouse gas.

2.2 IMAGE (An Integrated Model to Assess the Greenhouse Effect)

The tool we used is an integrated greenhouse assessment model: IMAGE. IMAGE is a model which links models from various scientific areas with policies for controlling global climate change. The model is meant for developing and evaluating long-term climate strategies and it calculates, on basis of historical and future emissions of greenhouse gases, the global temperature and sea level rise and ecological and socio-economic interests in specific regions. In IMAGE the climate change problem is modelled as a dynamic system with discrete time steps of half a year and a simulation period of 200 years, from 1900 to 2100. IMAGE itself is a concatenation of autonomously functioning models (modules): a world energy/economy model, atmospheric chemistry model, carbon cycle model, climate model, sea level rise model, an UVB-impact model and a socio-economic impact model. The backgrounds of the model are extensively described in Rotmans (1990). Figure 2.1 shows the modular structure of IMAGE.

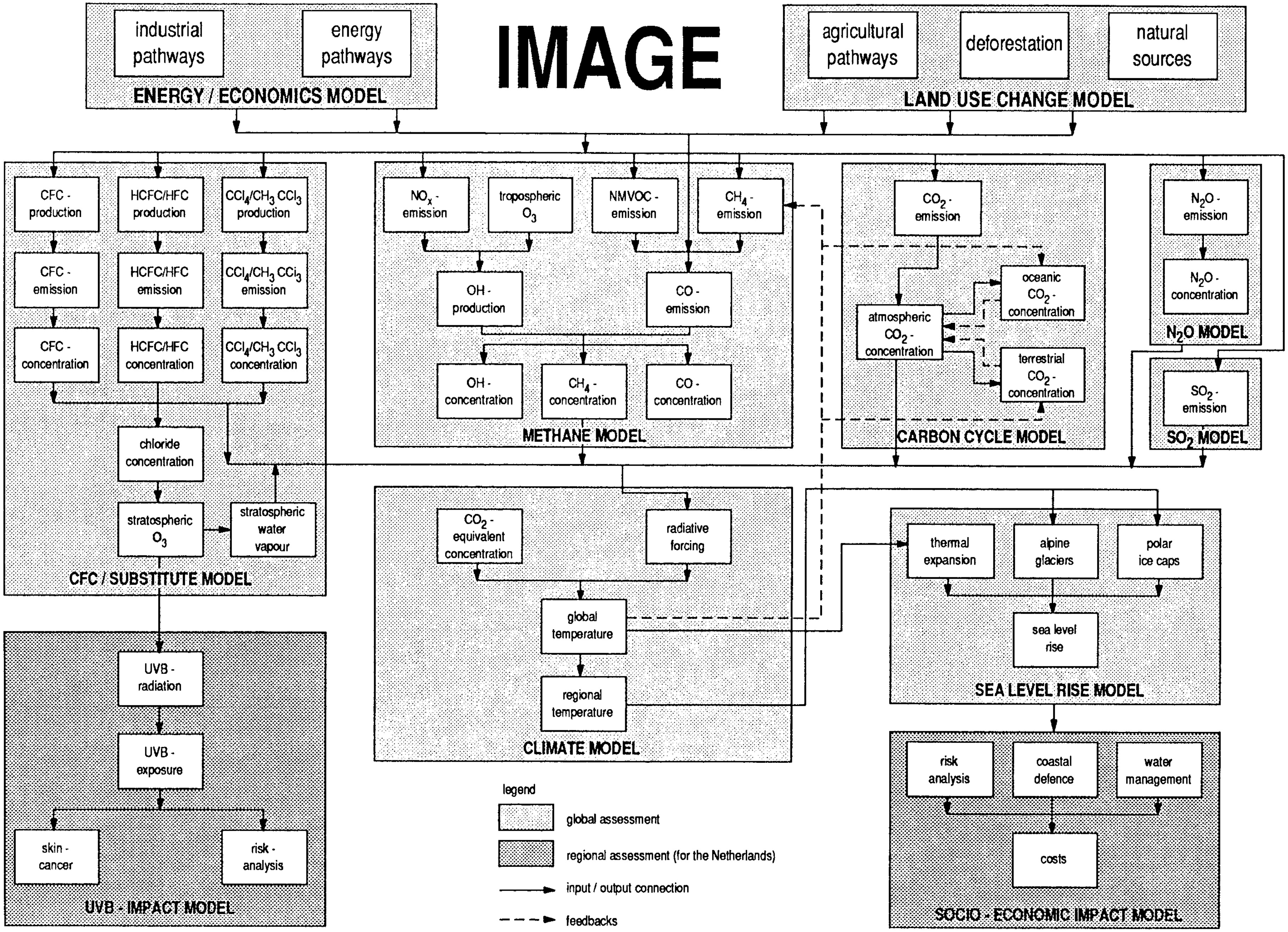

Figure 2.1
Structure of the Integrated Model for the Assessment of the Greenhouse Effect (IMAGE)

Although the integrated approach of IMAGE is conceptually attractive, it is a disputable one, because of the sequence of uncertainties consequent on the linkage of separate models, each with its own uncertainties. Therefore, IMAGE is an interpretive tool rather than a predictive tool, and is primarily meant to amplify our insights into the present and future driving forces behind global climate change. Below we describe briefly the basic structure of the separate modules of IMAGE and focus on the modules which are interesting for this study.

The global energy model of Edmonds and Reilly (1986) has been fully integrated into IMAGE. With this model long-term energy paths can be assessed by considering economic, demographic, technical and policy factors. The model version we used is disaggregated into nine regions: USA, OECD West, OECD Asia, Centrally Planned Europe, Centrally Planned Asia, Middle East, Africa, Latin America, and South East Asia. This is somewhat different from the subdivision in this study, in which we distinguish for OECD West: European Community and rest of Western Europe, for Centrally Planned Europe: Eastern Europe and USSR, and we combined USA and Canada to North America.

The natural carbon cycle encompasses exchanges of carbon dioxide between atmosphere, oceans and the terrestrial biosphere of hundreds of billions tons of carbon a year. The extra manmade emissions through land use changes and fossil fuel combustion is relative small compared through these tremendous quantities. The minor anthropogenic contribution is nevertheless supposed to account for the imbalance of the carbon cycle. This imbalance caused an increase in the CO_2 concentration. Because oceans and terrestrial ecosystems taken up a large amount, only about 40% of the anthropogenic emissions remains in the atmosphere. In the global carbon cycle there are still considerable uncertainties in our knowledge of the present sources and sinks for the anthropogenicaly produced CO_2. The carbon cycle model (Figure 2.2) consists of an ocean module, a terrestrial biota module, and a deforestation module. The ocean module is a modified, 12 layer version of a basic box-diffusion model (Björkström, 1979), where the transport of carbon is driven by massflow of water, turbulent mixing (diffusion), and precipitation of organic material. The terrestrial biosphere module within IMAGE is an extended version of the Goudriaan and Ketner model (1984). The terrestrial biosphere is divided horizontally into seven ecosystems. Vertically there is a distinction between biomass (subdivided into leaves, branches, stemwood and roots), litter, humus and charcoal. Furthermore, the deforestation process and its underlying causes are modelled separately in the deforestation module, where only the three major tropical forest areas are distinguished: Africa, Latin America and Southeast Asia. Deforestation is triggered by a variety of processes, which are mainly caused by demand for agricultural land to satisfy demand for food, feed or debt-resolving export products, driven by growth of population and economy (Swart and Rotmans, 1989, Rotmans and Swart, 1991).

For methane, a separate module is implemented, in which the CH_4-CO-OH cycle is simulated (Rotmans *et al.*, 1990). For the CFCs, a two-box delay model is used, while N_2O is simulated with a simple one-box module. The climate module is a parameterized radiative convective model, based on Wigley (1987). The effects of global warming on sea level are determined by thermal expansion of ocean water, the melting of ice caps (Alpine and Arctic), and the observed trend of a 10 to 15 cm per century sea level rise (Oerlemans, 1987). For the Netherlands, socio-economic impact modules have been developed, describing the consequences of an accelerated sea level rise (den Elzen and Rotmans, 1989). The UVB module describes the impact of decreasing stratospheric ozone on the skincancer incidence in the Netherlands.

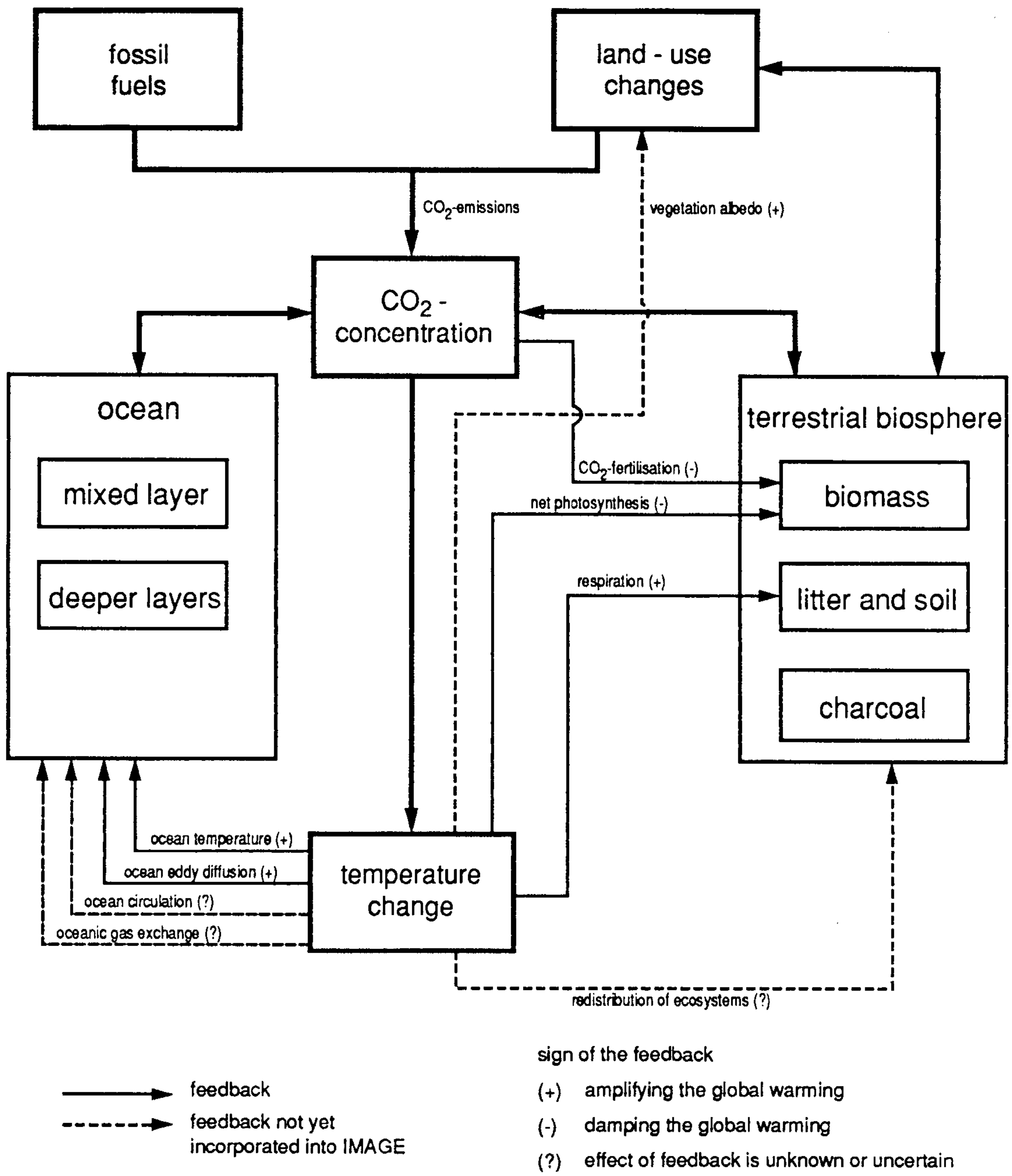

Figure 2.2
Carbon cycle

2.3 IPCC-scenarios

In 1989, the Response Strategies Working Group of the IPCC requested a US-Netherlands expert group to develop four different pathways for future global emissions of CO_2, CH_4, N_2O, halocarbons and the ozone precursors NO_x and CO. The expert group used two alternative models to construct these scenarios: the Atmospheric Stabilization Framework (ASF) developed by the U.S. EPA, and the Integrated Model to Assess the Greenhouse Effect (IMAGE) developed by the Dutch National Institute of Public Health and Environmental Protection (RIVM). For the development of these four scenarios, the expert group used the concept of the CO_2-equivalent concentration, defined as the concentration of CO_2 that by itself, would produce the increase in direct radiative forcing produced by all of the greenhouse gases under concern. Three scenarios were designed in such a way that they would lead to a doubling of the CO_2-equivalent concentration in the years 2030, 2060, and subsequently in 2090, called *Business-as-Usual* or *2030 High Emissions* scenario, *2060 Low Emissions* scenario and *Control Policies* scenario. The fourth scenario, the *Accelerated Policies* scenario, leads to stabilization of the CO_2-equivalent concentration at a level well below doubling of pre-industrial atmospheric CO_2. Figure 2.3[2] depicts the carbon emission scenarios due to fossil fuel combustion and land use changes between 1900 and 2100 according to the four scenarios, while Figure 2.4 illustrates the changes in the CO_2-equivalent concentrations.[3].

Each scenario is based on a set of assumptions for key factors influencing the future changes in emissions of greenhouse gases, including population growth, economic growth, the costs of technology used to convert energy from one form to another, end-use efficiency, deforestation rates, CFC emissions and agricultural emissions (IPCC, 1991). In the scenarios the reduction of energy intensity is the most important method of reducing carbon dioxide emissions.

The detailed backgrounds of the four IPCC scenarios are presented in Appendix 1. Here we will only briefly describe some of the basic assumptions on which the scenarios are based. The Business-as-Usual scenario assumes that few or no steps are taken to limit greenhouse gas emissions. Energy use and clearing of tropical forests continue to increase, and fossil fuels, in particular coal, remain the world's primary energy source. The Montreal Protocol is not strengthened and participation of the developing countries is assumed to be only 85 percent. The 2060 Low Emissions scenario assumes environmental concerns, which results in steps to reduce the growth of the greenhouse gas emissions; energy efficiency measures are implemented, the share of world's primary energy provided by natural gas increases; there is a full compliance with the Montreal Protocol and tropical deforestation is halted and reversed.

The Control Policies scenario reflects a world in which concern for climate change and other environmental issues results in steps over and above those taken in the 2060 Low emission scenario; technological development, commercialization, and governmental efforts result in rapid penetration of renewable sources in the last half of the next century.

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[2] The small decrease of emission at the end of this century is caused by the fact that the present emission are already higher then the original scenarios, which start in 1985.

[3] Present IMAGE calculations leads to higher concentrations, while recently CFC substitutes are implemented.

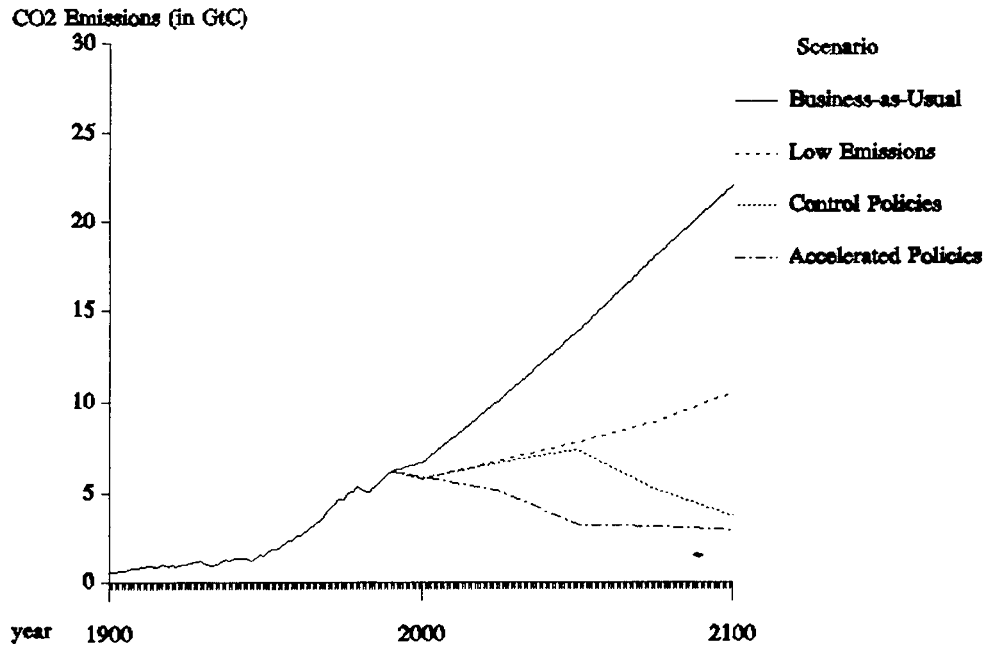

Figure 2.3: CO_2 emission by fossil fuel combustion.

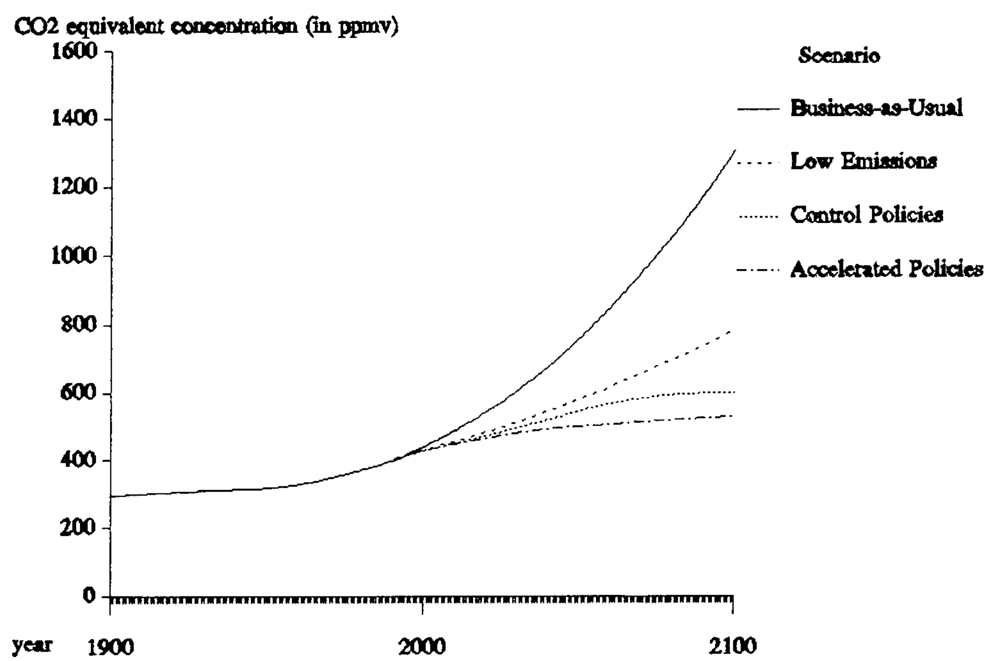

Figure 2.4: CO_2 equivalent concentration

The strengthened Montreal Protocol includes a phase-out of CFCs. As a result of agricultural policies, the emissions of CO_2, CH_4 and N_2O starts to decline in the middle of the next century. The Accelerated Policies scenario differs from the Control Policies scenario in that the development and penetration of renewable energy sources and nuclear energy is encouraged. This results in a decrease of the fossil CO_2 emissions after 2000, while the fossil related levels at the end of the next century are half those in 1985. In these scenarios deforestation will be stopped around the turn of the century and there will be a net increase in forests through large scale reforestation programmes. For the other greenhouse gases the assumptions are largely the same as in the Control Policies scenario.

2.4 Quantitative Targets for Climate Strategies[4]

As a tool for developing global climate strategies which limit the effects of climate change the Advisory Group on Greenhouse Gases (AGGG) identified several climate objectives (targets), in order to protect the structure and functions of vulnerable ecosystems. These targets relate in particular stages within the cause-effect chain, starting with the emissions due to human activities and ending with impacts on society and ecosystems, for example a limitation of the rate and magnitude of the temperature change or sea level rise (AGGG, 1990). In this study we adopt three climate targets, temperature targets of AGGG (1990) and the target of stabilizing concentrations of greenhouse gases as proposed by Swart *et al.* (1989), summarized:

1. *concentration stabilization target* (Swart *et al.*, 1989), stabilization of the CO_2-equivalent concentration at a level of a doubled pre-industrial atmospheric CO_2 (560 ppmv) at the end of the next century. This target can serve as a monitoring instrument and as a basis or possible adjustments of emission control policies.
2. *absolute temperature target* (AGGG, 1990), limit maximum of the absolute temperature increase of 2 °C above pre-industrial global mean temperature. This temperature limit can be viewed as an upper limit beyond which the risks of considerable damages to ecosystems and sensitive coastal areas, and of unexpected sudden changes in the climate system, are expected to increase rapidly.
3. *relative temperature target* of 0.1 °C per decade (AGGG, 1990), which would allow for adaptions of ecosystems (Jäger, 1988).

The concentration stabilization target can be seen as a target, which future policies should comply in order to reduce anticipated risks of climate change to acceptable levels. The absolute temperature target reflects a world, in which risks of climate change has reduced to a low level, while the relative temperature target reduces to a minimum (sustainable level) and leading to a sustainable world. Achieving these sustainable targets requires the implementation of policies that will involve stabilizing or reducing emissions of greenhouse gases. There is growing evidence that the first steps towards this goal will not be very costly (RIVM, 1991). In fact, they are probably profitable and often serving other desirable goals as well.

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[4] This section is primarly based on *'Halting Global Warming: Should Fossil Fuels be phased out?'* by J. Rotmans and M.G.J. den Elzen (1992).

We developed an adapted version of the *Control Policies scenario* in order to meet the *concentration stabilization target*, which only differs with the original Control Policies scenario in CO_2 emissions. Here we assume a further linear reduction of the CO_2 emissions after 2025 till 50% relative to 1985 in 2100.
Rotmans and den Elzen (1992) have evaluated the four IPCC scenarios (IPCC, 1991) with respect to sustainable climate targets of AGGG (1990). The results indicate that according to all IPCC scenarios the standards for sustainability, defined as relative temperature target above, will be exceeded. Even in the Accelerated Policies scenario the 0.1 °C per decade will be exceeded from 1960 to 2035, however, the *Accelerated Policies scenario* achieves the *absolute temperature target.* The corresponding CO_2-equivalent concentration is 530 ppmv. Rotmans and den Elzen (1992) developed with IMAGE an alternative scenario that comply the sustainable standard: the *Aggressive Policies scenario.* In order to meet this *relative temperature target,* the CO_2-equivalent concentration had to be stabilized at the lowest possible level in the shortest possible time. This implies for CO_2 a 50% reduction according to the Toronto guidelines (WMO, 1988), for methane a 20% reduction, for nitrous oxide 30% reduction of the anthropogenic emissions and for CFCs a full phase-out. The final CO_2-equivalent concentration leads to a level of 475 ppmv in 2100.
Summarily, to achieve the three formulated targets, the emissions of the greenhouse gases should follow respectively the IPCC adapted Control scenario, IPCC Accelerated Policies scenario and the Aggressive Policies scenario. Figure 2.5 depicts the carbon emissions of the target scenarios, while the resulting CO_2-equivalent concentration levels are shown in Figure 2.6. Figures 2.7 and 2.8 comprise the induces climate risks for the three scenarios: the rate of temperature increase and the absolute temperature increase.

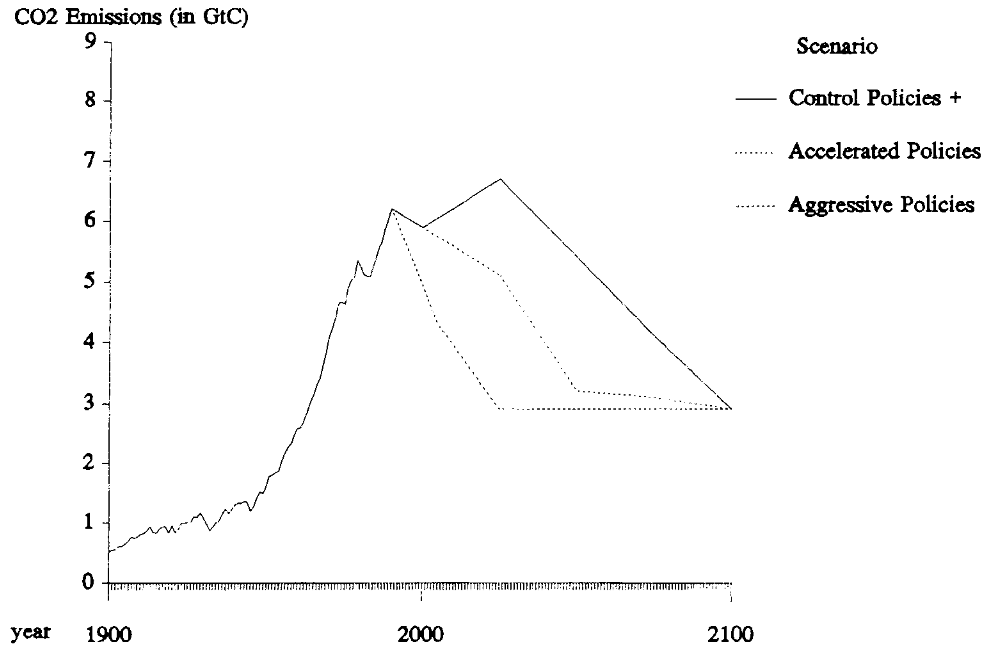

Figure 2.5: CO_2 emissions by fossil fuel combustion.

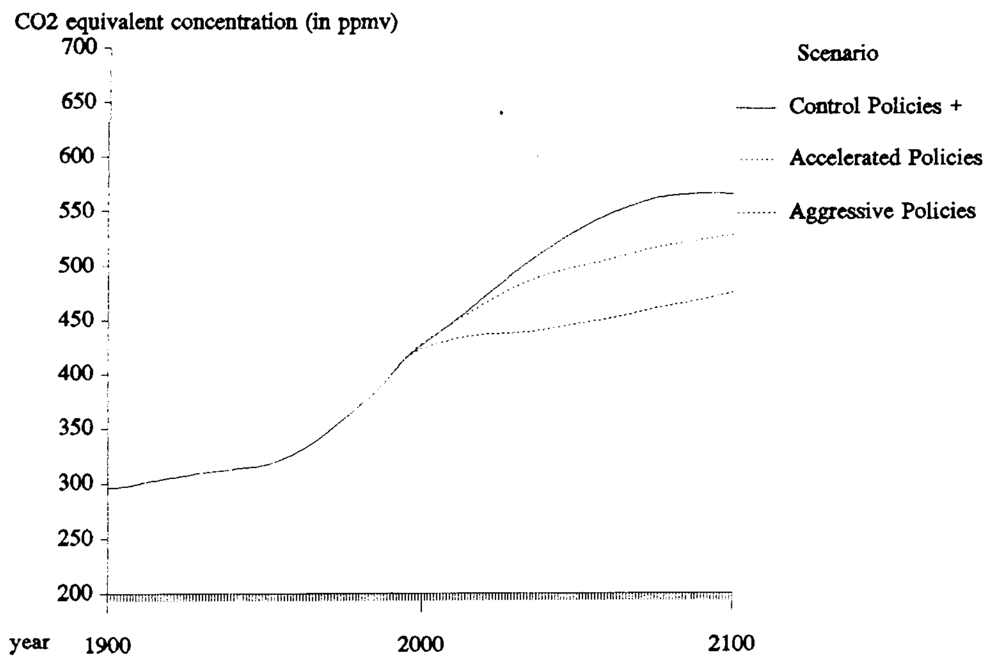

Figure 2.6: CO_2 equivalent concentration.

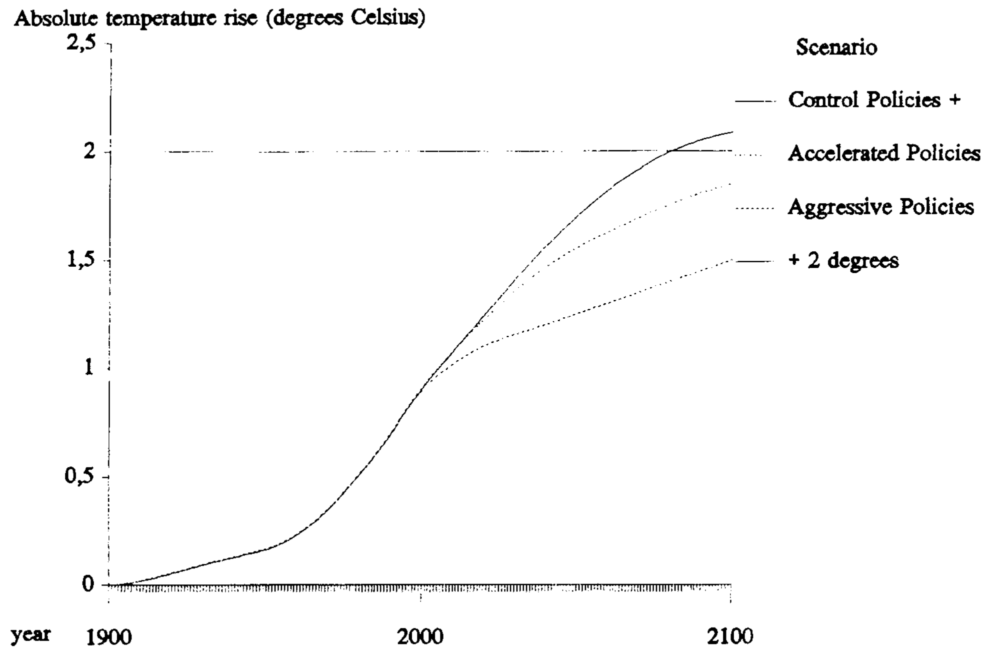

Figure 2.7: Absolute temperature rise.

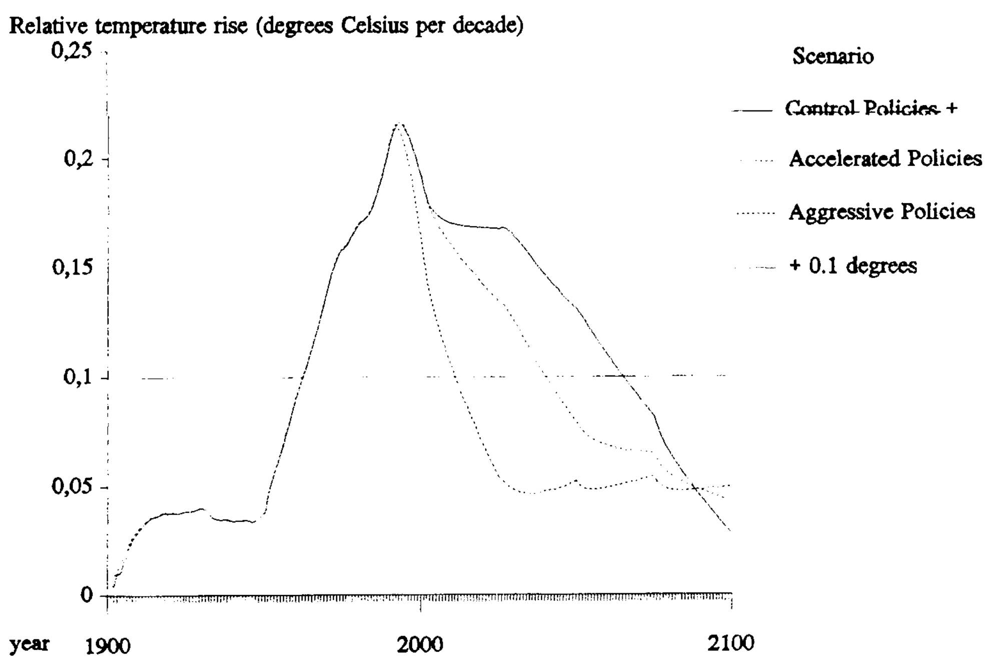

Figure 2.8: Relative temperature rise per decade.

2.5 Delayed Response Strategies

To underscore the importance of rapid decision making, we performed an analysis in which the start of international response actions are delayed from present to 2000, 2010, 2020 and 2030, respectively. The greenhouse gas emissions are assumed to follow the emissions of the Business-as-Usual scenario where no action is taken to limit greenhouse gas emissions. Furthermore, it is assumed that when international response is taken and followed up to start controlling climate change, the policy target will be concentration stabilisation target, as described in section 2.4. Emissions of non-CO_2 trace gases are assumed to be deflected towards the values associated with the IPCC Control Policies scenario. The emission paths of CO_2 have been determined after many simulation-runs, and depicted in Figure 2.9. It appears that waiting with actions leads to larger reductions in shorter time intervals. Waiting until 2000 obliges a reduction of 50% of 2000-level in 60 years while waiting till 2010 leads to a reduction of 60% of 2010-level in 40 years. When actions are delayed till 2020 a reduction of 65% of 2020-level in 10 years is necessary in order to reach the target. As can be expected, delaying response until 2030 would render a complete and prompt phase-out of CO_2 emissions from fossil fuel combustion. Even a slight increase of the emissions is permitted during the second half of the next century to reach stabilization, because a continuing decrease of the emissions should result in decreasing concentrations instead of stabilizing concentrations. The resulting changes in atmospheric composition for the delayed response scenarios, as calculated by IMAGE, are represented in Figure 2.10.

Earlier comparable delayed response analysis with IMAGE showed a smaller emission reduction over a longer time-period (Rotmans and Swart, 1990) as is showed in Figure 2.11. This can be explained by the fact that recently CFC-substitutes and methane feedbacks are implemented in the model, both leading to a further increase of the CO_2-equivalent concentrations. Besides, non-CO_2 gases were assumed to follow the Control Policies scenario over the whole period in their study, and they used a stabilization target based on a CO_2-equivalent concentration of 570 ppmv.

The delayed response analysis shows that, if social and economic consequences are taken into consideration, actions can not be delayed. Further waiting leads to unrealistic reductions necessary to reach the targets. Because the social and economic circumstances differ among regions, also the allocation to regions is needed to be considered. The global reduction paths to meet climate targets and their allocation over the regions will be one of the main issues investigated in this study.

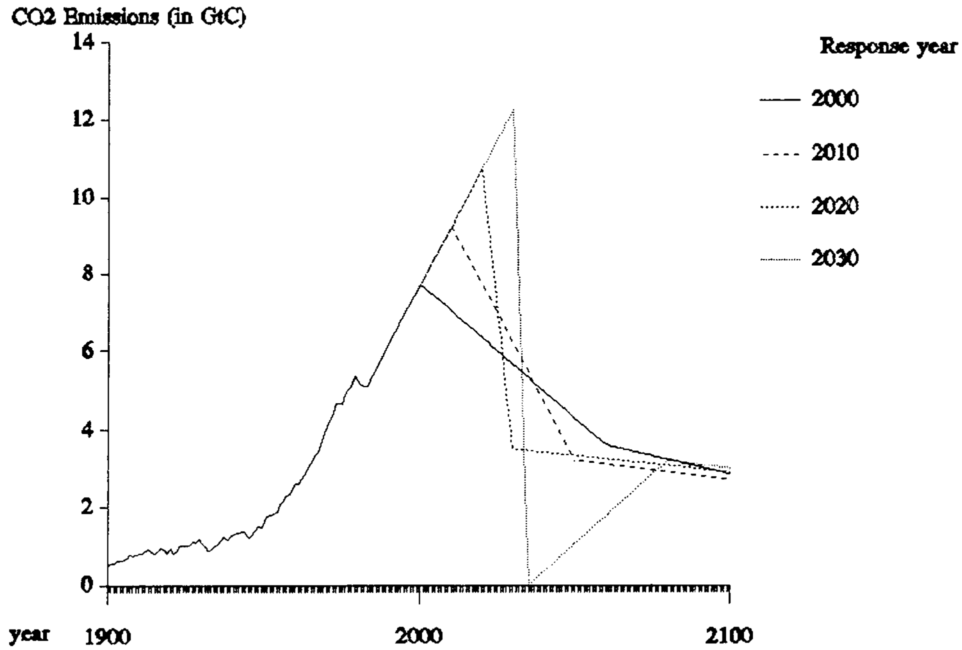

Figure 2.9: Emission scenarios for different starting times of international response

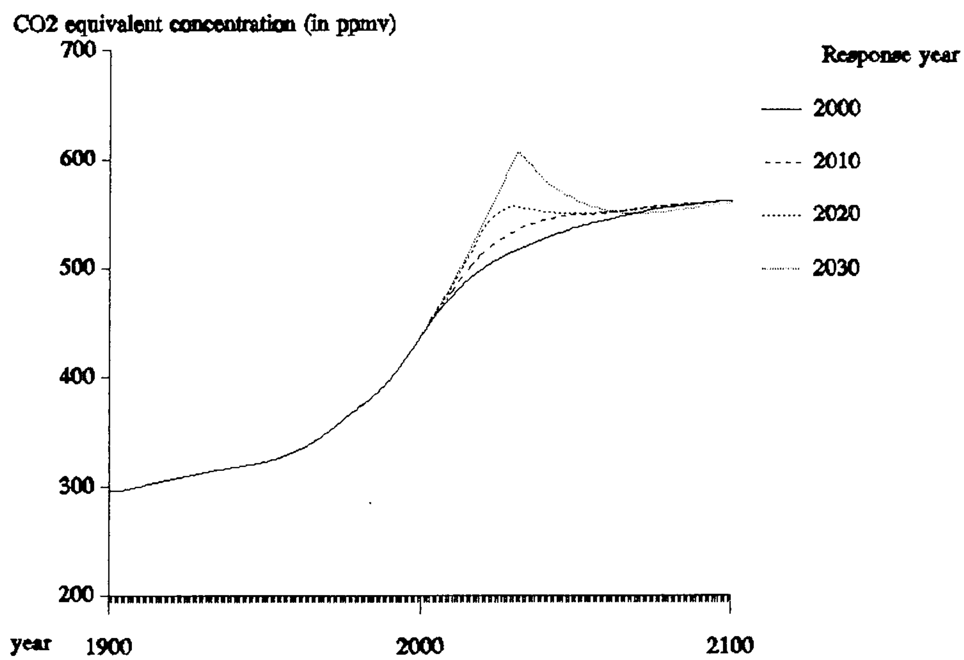

Figure 2.10: Concentration values of delayed response scenarios.

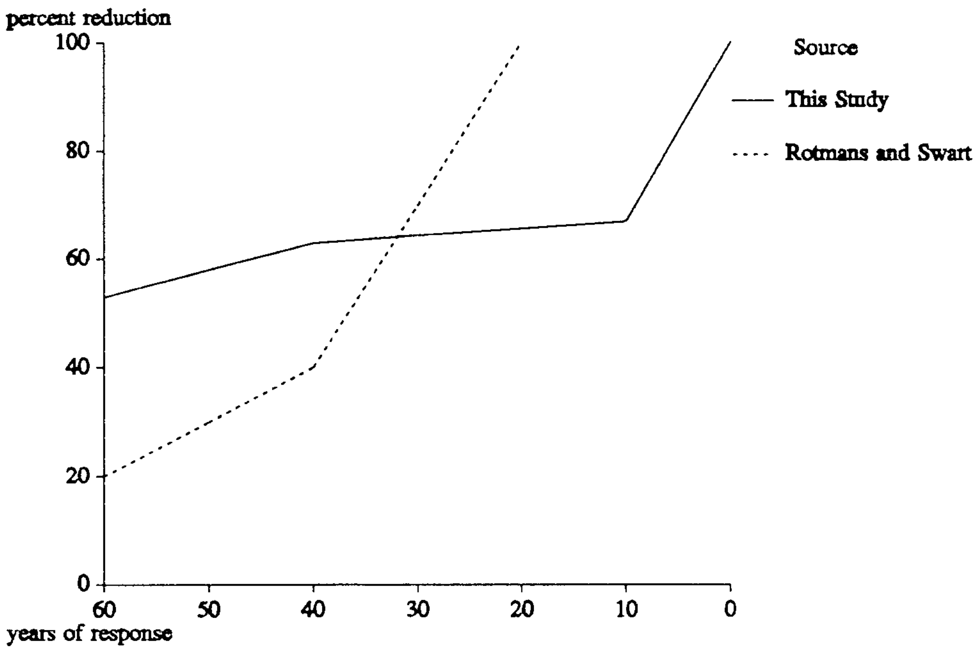

Figure 2.11: Effect of delaying international response on the time to reduce emissions and the amount of the needed reductions.

3 Emission Debt

3.1 Introduction

The feasibility of an effective international response to the anticipated climate change is dependent on the recognition of the present and historical inequities between developing and industrialized countries. Developing countries should be enabled and supported to continue their development towards higher standards of living in a fashion that is consistent with the sustainability of the global biosphere. In this chapter we introduce the concept of 'emission debt' based on an equal share per capita per year irrespective of both the country he or she lives in and the generation he or she belongs to. Further we evaluates regional emission budgets which meet the sustainable targets as defined in section 2.4 and in which the global effort of controlling climate change is shared on an equitable basis, which provide for intergenerational and international equity throughout the world.
The structure of this chapter is as follows. Firstly we start with an estimation of the regional historical carbon dioxide emissions due to fossil fuel combustion and land use changes in the different regions (section 3.2). For other greenhouse gases we have not made an estimation of the historical regional emissions, because of lack of sufficiently reliable data. Then we present in section 3.3 the regional contributions to the past rise in the CO_2-concentration calculated with the IMAGE-model.
In section 3.4 we introduce two methods to calculate an equal emission quota which determines emission debt. The first method is called the intergenerational approach and is based on an emission scenario, where everybody living between 1800 and 2100 emit an equal emission quota per year, which lead to a target related concentration level. The second method is the global carbon budget approach in which the equal emission quotum is the same as the averaged amount of carbon per capita per year of a global carbon budget, which is equal to historical emissions and emissions of a scenario which leads to a climate target.
Finally, section 3.5 presents results of regression analyses between the relative contribution of cumulative historical regional emissions, emission debt and present financial external debt.

3.2 Regional Historical Carbon Dioxide Emissions

3.2.1 Introduction

In this section, we examine the regional CO_2 emissions over the time period 1800 till now, from fossil fuel combustion (plus minor industrial sources like cement production) and changes in land use such as deforestation, which primarily caused the observed increase in atmospheric CO_2. As already explained in section 2.2. we distinguish eleven regions: European Community (EC), Rest of West Europe (RW.Eur.), OECD East (OECD E.), Eastern Europe (E.Eur.), USSR, North America (N.Am.), Latin America (Lat.Am.), Africa, Middle East (M.East), Centrally Planned Asia (CPA) and South/Southeast Asia (SSEA).
The here described estimation is based on an intensive study of literature on fossil fuel use and land use changes in the past. Since the national borders of many countries have been changed over the time period 1800 till 1990, and data were only available on national scale, some adaptions had to be made for calculating the historical CO_2-emissions for each region (with fixed borders over whole time period). The emissions of East Europe, USSR and Rest of West Europe have been slightly adapted, because of the forming of Czechoslovakia in 1918 and Poland in 1914, which before that time belonged mainly to respectively Austria and Russia. The correcting method is straightforward: we trace back the emissions before 1920, based on the relative distribution in 1920.

3.2.2 Fossil Fuel Combustion

The global annual emissions of CO_2 from fossil fuel burning and minorly cement manufacturing[1] (less than 2 percent) has shown an exponential increase since 1800 (about 4% yearly), with major interruptions during the two world wars and the economic crisis in the thirties (see Figure 3.1). The cumulative release of CO_2 from fossil fuel use and cement manufacturing from 1850 to 1987 is estimated at 200[2] GtC $\pm$ 10% (Marland, 1989). In 1989 the global emission was about 5.9 billion tonnes of carbon (Marland, 1989). However, there is a main difference between the contribution of the industrial countries and the developing countries; about ninety five percent of the industrial CO_2 emissions are from the Northern Hemisphere, where annual releases reach up 5 tC per capita (Rotty and Marland, 1986). Contrary, the CO_2 emissions in most developing countries lie between 0.3 and 0.6 tC per capita per year, although the relative rate of increase in the developing countries is much larger (about 6% per year). The historical CO_2 emissions before 1800 by fossil fuel combustion is although unknown, expected to be small while the fossil fuel consumption in 1800 is already very low (Mitchell, 1981) and thus has a negligible contribution to the present observed atmospheric CO_2-increase.

[1] Carbon emissions of cement manufacturing are incorporated in the emission flux due to fossil fuel combustion, except if it is specially noted.

[2] 201 GtC in this study.

In Table 3.1. we summarize the literature sources we use, as well as the motivation.

Source	Time period	Data	Motivation period used
Mitchell (1981, 1982,1983)	1800 - 1975	Production and in- and export	only almost complete source of national data for Europe, USSR, North/South America. before 1920
Darmstadter (1971)	1925 - 1965	Consumption	source of national data for world. 1920-1950
Marland *et al.* (1989)	1950 - 1989	CO_2-emissions	standard IPCC source, national data. after 1950

Period 1800 - 1925:

Over the period 1800 till 1925 the consumption data of coal, petroleum and gas in Western-Europe[3], Eastern-Europe, North America and Latin America and USSR (Russia) are calculated by counting the domestic production and net imports of the historical statistics of Mitchell (1981, 1982 and 1983) at intervals of five years. While no import data of natural gas is available, the consumption of gas in each region is assumed to be equal to its production. Mitchell (1981, 1982, 1983) does not give import/export data for the other regions in the world (minor important share in the world consumption), we calculate their share based on the difference in the total world consumption (assumed to be equal to world production) and the total consumption of Europe, USSR and North and Latin America. The allocation to these different regions is based on their relative contribution in 1925 given by Darmstadter (1971). For converting all the regional consumption data of the fossil fuels into regional CO_2 emissions, we use the conversion factors of Ausubel *et al.* (1988).

The total global CO_2 emissions calculated from the world fossil fuel production data of Mitchell (1981, 1982, 1983) differs from the global emission data in IMAGE based on Watts (1982) with 1-2%, thus within the uncertainty range of 10 percent (Marland (1989)) (see Figure 3.1).

Period 1925-1950:

For the period between 1925 and 1950, the consumption data for coal, petroleum and natural gas of all our world-regions are given in Darmstadter (1971). While, in spite of Mitchell's statistics, these data are consumption estimates and covers the whole world, we base our regional consumption data for this period on Darmstadter's statistics. Analogous to the calculations of the CO_2 emissions over the period 1800 till 1920, we calculate the regional CO_2 emissions based on the conversion factors of Ausubel *et al.* (1988).

The global calculated CO_2 emissions from Mitchell (1981, 1982, 1983) over the period

[3] The consumption data of coal in some Western-European countries, like Great Brittain, Belgium are extrapolated between 1800 and 1815.

1920 and 1950 are significantly higher then the global CO_2 emissions derived from Darmstadter (1971), but are still within the uncertainty range of 10% over this period (see Figure 3.1). The global CO_2 emission data used in IMAGE, based on Marland and Rotty (1984) and Rotty (1987) are lying between both sources.

Period 1950-1990:

The regional CO_2 emission data between 1950 and 1989 are based on the IPCC reference literature source; Marland *et al.* (1989).

The global CO_2 emissions over the period 1950 and 1989 are not equal to the global CO_2 emissions derived from the regional data, although both based on Marland *et al.* (1989). Marland *et al.* explained this difference, which is less then the uncertainty range of 5% for the last decades, in the fact that for the global estimates UN production data and for the national estimates UN international trade estimates were used. Both UN sources differ for two reasons; different treatments of non-fuel-use are used in the global and national calculations and the inclusion of fossil fuels stored in bunkers has only been made in the national estimates. Other literature sources for the regional CO_2 emissions over the recent period 1985 and 1990, like WRI (1990/1991) and Brittish Petroleum Inc (1990) give regional CO_2 emission profiles within the uncertainty range given by Marland *et al.* (1989).

Finally the emissions between 1900 and 1990 are scaled to obtain the same global emissions fluxes as used in IMAGE. The regional fluxes are depicted in Appendix 2.

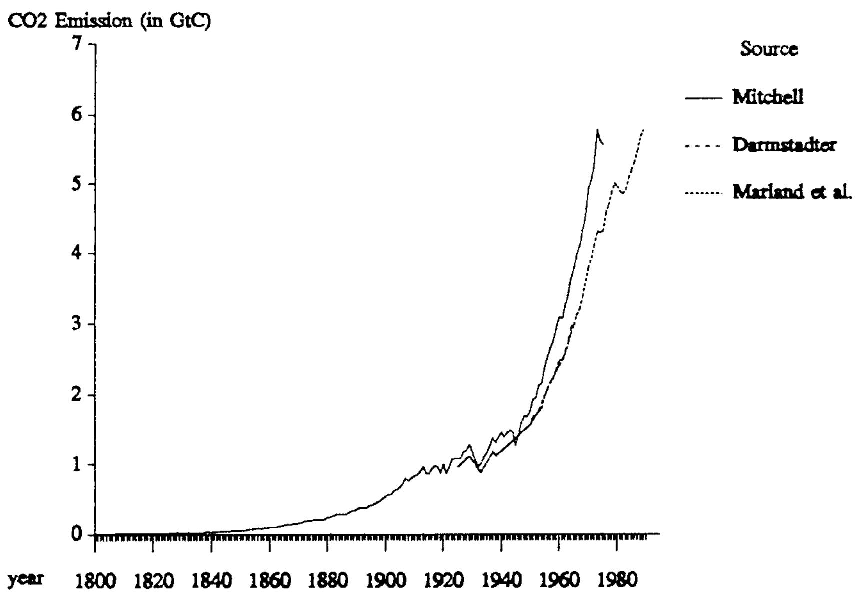

Figure 3.1: Different data sources for different periods used to estimate emission fluxes due to fossil fuel combustion and cement production.

3.2.3 Land Use Changes

3.2.3.1 Introduction

Changes in land use over the past two centuries have caused a significant release of CO_2 to the atmosphere from terrestrial biota and soils. About one third of the carbon emissions is thought to have come from deforestation (Siegenthaler an Oeschger, 1987; Houghton and Skole, 1990). Before 1900 the emissions through deforestation were even greater than those from fossil fuels. Europe, North America and Russia have caused the largest contributions in the last century of emissions through expansion of croplands. In this century deforestation in temperate and boreal zones has slowed down, while in tropical regions it has accelerated. The tremendous pressure from increasing demands of growing populations is the major cause of this accelerating deforestation. The result of the large destruction of rainforest is the extinction of species, increased erosion, threats to indigenous people, the modification of regional and even global climate and the destruction of a wide variety of possible important assets.
Estimates of carbon emissions from land use changes depend on the amount of carbon in soil and biomass, rates of oxidation of wood products (through burning or decay), rates of decay of organic matter in soil and the rates of land use changes. In this study the net release of regional carbon emissions due to land use changes has been estimated using different data sources.
In this section the rates of deforestation and the estimates of the regional carbon emissions are discussed first. Thereafter uncertainties of the estimated carbon fluxes due land use changes are given.

3.2.3.2 Rates of Conversion of Ecosystems

The changes in the carbon storage are mainly caused by forest clearing, which convert forest to permanent agriculture and pasture. Selective logging and shifting cultivation are much smaller (Detwiler and Hall, 1988). The rates of land use changes for the period between 1800 and 1980 are derived from Houghton *et al.* (1983). They distinguish in their study 14 ecosystems (see Table 3.2 and Appendix 3). The area's of the ecosystems for 10 regions are given for their starting year 1700. Also the rates of conversion of ecosystems are given for the period between 1700 and 1980 in different subperiods. The different kinds of conversion are (Figure 3.2): agricultural clearing, abandonment of agriculture, afforestation and clearing for pasture. The rates of conversion are based on estimates from an intensive literature study and on population growth. Also other rates for the period between 1950 and 1980 are presented in Houghton *et al.* (1983), based on FAO data and on rates of clearing of tropical forests offered by Myers (1980a,b), which are respectively lower and higher than population based rates. Because regions of Houghton *et al.* are not the same as used in this study, some assumptions are made to estimate the emissions for regions as used in this study[4].

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[4] The emissions of Europe are divided according to the ratio of land area, assuming that the rates of change and the distribution of ecosystems in the European regions have been homogeneous. The 'OECD East' emissions are assumed to be equal to 'Pacific developed'. The regions USSR, North and Latin America are the same in both studies. Assuming the rates of change and the

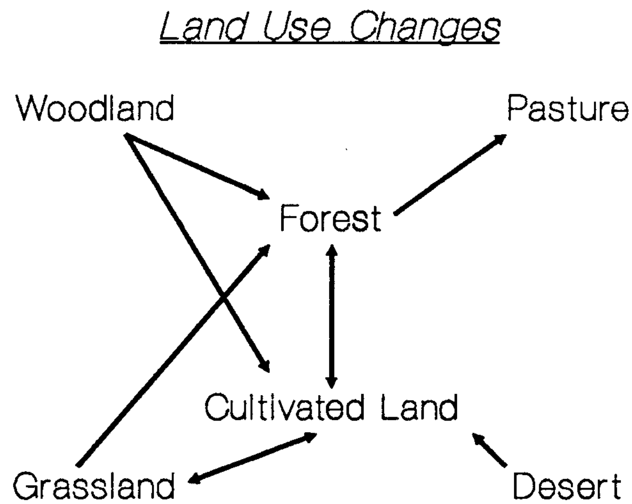

Figure 3.2: Scheme of conversion of ecosystems as used in Houghton *et al.* (1983)

For the period between 1980 and 1990 Houghton *et al.* rates are extrapolated. Except for tropical regions, the rates of conversion are assumed to be the same as 1980. In the tropical regions, the rates of conversion of ecosystems are adapted following estimates from Swart and Pepper (1991) and Swart *et al.* (1991), which are based on FAO data (FAO, 1988,1991). Because their classification is different from that of Houghton *et al.* (1983), we have distributed rates of forest clearing proportional to the deforestation rates of Houghton *et al.* ecosystems.
The estimated land use of the different regions using the above rates of conversion are summarised for different years in Appendix 3.

3.2.3.3 Estimating the Carbon Emissions

We have used, according to Houghton *et al.* (1983), a bookkeeping model, which account of the yearly changes of carbon in ecosystems, to estimate the carbon emissions through land use changes. The carbon release is estimated by using estimates of carbon in soil and vegetation before and after the change of land use (Table 3.2). The duration of the carbon changes in the forest soils depends on their use after clearing, however, these time lags are neglected because of the relative short lags.
The data to define the changes in the carbon in vegetation and soils during the transformation of a natural ecosystem to agriculture and following abandonment are enumerated in Table 3.2. (Houghton *et al.*, 1983), including adaptions from Houghton *et al.* (1987). These adaptions are a raising of the carbon content in soil by 50% and using specific data for the USSR.

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distribution of ecosystems homogeneous for the regions North Africa and Middle East, these emissions are divided according to the ratio of land area. Adding up Tropical and North Africa emissions results in the carbon flux of Africa. Centrally Planned Asia emissions are assumed to be equal to the region China, and for the region South/Southeast Asia emissions are assumed to be equal to the total of Houghton *et al.* (1983) regions South and Southeast Asia.

Agricultural clearing :

When a ecosystem is cleared for agriculture the carbon of the vegetation decrease to values of the crops. The carbon in soils decreased to a minimum value. This value is dependent of the original ecosystem. The relation used to estimate the emissions from agriculture clearing is given in equation 3.1.

$$AGREM(t) = \Sigma_e\ AGR(t,e) * (CARVEGUN(e) + CARSOILUN(e) - CARCROP(e) - MINCARSOIL(e)) \quad (3.1)$$

with:

AGREM(t)	= Emissions of change from ecosystems to agriculture (10^{12} g/yr)
AGR(t,e)	= Rate of change from ecosystems to agriculture (10^6 ha/yr)
CARVEGUN(e)	= Carbon in vegetation of undisturbed ecosystems (10^6 g/ha)
CARCROP(e)	= Carbon in crops (10^6 g/ha)
CARSOILUN(e)	= Carbon in soils of undisturbed ecosystems (10^6 g/ha)
MINCARSOIL(e)	= Minimum carbon content of soil in cultivated system (10^6 g/ha)
e	= ecosystem
t	= year

Abandonment of agriculture :

Abandonment of agriculture increase the carbon values to these of recovered systems (3.2).

$$ABANEM(t) = \Sigma_e\ ABAN(t,e) * (CARCROP(e) + MINCARSOIL(e) - CARVEGREC(e) - CARSOILREC(e)) \quad (3.2)$$

with:

ABANEM(t)	= Sequestration of abandonment of agriculture (10^{12} g/yr)
ABAN(t,e)	= Rate of change from agriculture to ecosystems (10^6 ha/yr)
CARVEGREC(e)	= Carbon in vegetation of "recovered" ecosystems (10^6 g/ha)
CARSOILREC(e)	= Carbon in soils of "recovered" ecosystems (10^6 g/ha)

Afforestation :

When afforestation occurs in boreal and temperate zones, ecosystems changes from an ecosystem to temperate evergreen forest. Because afforestation causes a conversion from a low into a high carbon containing ecosystem, this leads to a uptake of carbon by the terrestrial biota. The relation used to estimate carbon uptake from afforestation is formula (3.3).

$$AFFEM(t) = \Sigma_e\ AFF(t,e) * (CARVEGUN(e) + CARSOILUN(e) - CARVEGREC(tef) - CARSOILREC(tef)) \quad (3.3)$$

with:

AFFEM(t)	= Sequestration of afforestation (10^{12} g/yr)
AFF(t,e)	= Rate of afforestation (10^6 ha/yr)
CARVEGREC(tef)	= Carbon in vegetation of recovered temperate evergreen forest (10^6 g/ha)
CARSOILREC(tef)	= Carbon in soils of recovered temperate evergreen forest (10^6 g/ha)

Table 3.2 The data used to define the changes in the carbon in vegetation and soils during the transformations to agriculture. Values unique to the analysis of the USSR are shown in parentheses. Houghton *et al.* (1983,1987)

	Tropical moist forest	Tropical seasonal forest	Temperate evergreen forest	Temperate deciduous forest	Boreal forest	Tropical woodland shrubland	Temperate woodland shrubland	Tropical grass-land	Tem perate grass-land	Desert Scrub
Carbon in vegetation of undisturbed ecosystems (10^6 g/ha)	200	160	160	135	90	27	27	18	7	3
Carbon in vegetation of "recovered" ecosystems (10^6 g/ha)	150	120	120	100 (108)	68 (72)	27	27 (10)	18	7 (10)	3
Carbon in crops (10^6 g/ha)	5	5	5	5	5	5	5	5	3	1
Carbon in soils of undisturbed ecosystems (10^6 g/ha)	117	117	134	134	206	69	69 (189)	42	189	58
Carbon in soils of "recovered" systems (10^6 g/ha)	88	88	120	120 (134)	185 (206)	69	69 (189)	42	189	58
Minimum carbon content of soil in cultivated system (10^6 g/ha)	87	87	100.5	100.5 (107)	154.5 (165)	51.75	51.75 (151)	31.5	141.75 (151)	130.5

<u>Clearing for pasture</u> (only in Latin America)

Only in Latin America clearing for pasture occurs. Houghton *et al.* (1983) data of these rates of conversion are based on population (1950) and FAO data for 1970 and 1980. The carbon flux through deforestation in 1950 was, much higher than in the seventies, which is in contrary to WRI data (WRI, 1988/1989), where the emissions of biotic sources in Latin America have been growing with a fast rate. Therefore we leaved the conversion to pasture rate in 1950 out of the data.
When forest is cleared for pasture, the carbon in soil declines from an undisturbed level to the minimum level and carbon in vegetation after clearing is assumed to be equal to tropical grassland. To estimate the emissions we used formula (3.4)

$$PASEM(t) = \Sigma_e \, PAS(t,e) * (CARVEGUN(e) + CARSOILUN(e) - CARVEGREC(tgl) - MINCARSOIL(e) \qquad (3.4)$$

with:
PASEM(t) = Emissions of change from forest to pasture (10^{12} g/yr)
PAS(t,e) = Rate of change from tropical grassland to pasture (10^6 ha/yr)
CARVEGREC(tgl) = Carbon in vegetation of "recovered" tropical grassland (10^6 g/ha)

<u>Total emissions :</u>

The total carbon flux due to land use changes is the sum of the four kinds of conversion.

$$LUCEM(t) = AGREM(t) + PASEM(t) + ABANEM(t) + AFFEM(t) \qquad (3.5)$$

with:
LUCEM(t) = Carbon Emissions by landuse changes (10^{12} g/yr)

The resulting regional estimates of carbon emissions by land use changes are depicted in Appendix 2. The global CO_2 emissions are depicted in Figure 3.3[5].

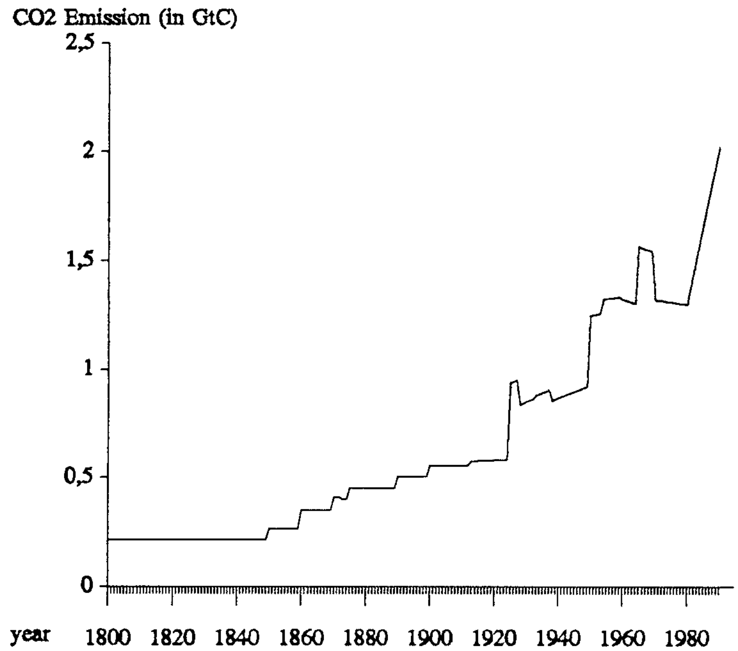

Figure 3.3: Global emission by land use changes

3.2.3.4 Uncertainties

Houghton (1991) gives four factors which cause uncertainties in estimating carbon fluxes by land use changes. Firstly, rates of deforestation differs among several studies, which are caused by differences in purpose and in definition. Secondly, large differences in estimates of carbon stocks cause uncertainties. Estimates of those stocks vary by almost 100%, which may be caused by errors in conversion factors and differences in surveys. Thirdly, differences caused by the fate of deforested land or land use. Is deforestation permanent or temporary? Finally, uncertainties are caused by exchanges of biotic CO_2 which are not associated with deforestation.
Comparison with other studies show the large uncertainties of estimating carbon emissions by land use changes (Table 3.3). The fluxes derived in this study for 1980 are within the uncertainty ranges of other studies, which is also the case in 1990 with fluxes in tropical regions (Table 3.3). IPCC (1990) give an 1850-1986 estimate of 117 $\pm$ 35 GtC, while our estimate over this period amounts 107 GtC.
The deforestation module of IMAGE, where only the regions Tropical America, Tropical Africa and Tropical Asia are modelled, which contributes 80% of the carbon emissions in this study between 1900 and 1990, is a simulation model where the underlying driving

[5] The stepwise emission paths are caused by the period rates of conversion by Houghton *et al.* (1983).

forces are modelled separately. The net flux of carbon is estimated for comparison with this study using the data of Table 3.2. This results in a lower flux than estimates in this study, although they have the same trend (Appendix 4). The carbon emissions in the eighties from IMAGE results are 1.3 GtC/yr, where our estimates results in 1.6 GtC/yr. Note that these estimates are both within the range of uncertainty from 0.6 GtC/yr to 2.6 GtC/yr (IPCC, 1990).

The global emissions of biotic source from the WRI data (WRI, 1988/1989) have the same trend as our estimates, although no significance drop occurs during the seventies in the WRI data (Appendix 4). Also the African emissions are somewhat lower and the emissions of North America, Europe and China are somewhat higher (WRI, 1988/1989).

Table 3.3 Ranges of carbon fluxes by land use changes from different studies (in GtC).

Sources	1980 World	1980 Tropical regions	1980 Temperate and boreal regions	1990 Tropical regions
Moore *et al.* (1981)	2.2 - 4.7	1.8 - 3.8	0.4 - 0.9	
Houghton *et al.* (1983)	1.8 - 4.7	1.3 - 4.2	0.5	
Houghton *et al.* (1985)		0.9 - 2.5		
Houghton *et al.* (1987)	1.0 - 2.6		0.1	
Molofsky *et al.* (1984)		0.6 - 1.1		
Detwiler *et al.* (1985)		1.0 - 1.5		
Detwiler and Hall (1988)		0.4 - 1.6		
Hao *et al.* (1990)		0.9 - 2.5		
Armentano and Ralston (1980)			-1.0 - -1.2	
Johnson and Sharpe (1983)			-1.6 - -1.9	
Houghton (1991)				1.1 - 3.6
Swart *et al.* (1991)				1.7
IMAGE		1.2		1.3
This study	1.2	1.3	-0.1	2.1

3.3 Regional Historical Contribution to increased CO_2-Concentration

Until now industrialized countries have contributed much more to carbon dioxide emissions than the developing world. Using the IMAGE model, which is described in chapter 2, we estimated each region's contribution to the global increase in the CO_2-concentration since 1800[6,7], both from fossil fuel use, and from land use changes. This has been done by calculating the difference in concentration increase with and without the emissions of the region under concern.

Figure 3.4 shows the relative contributions to the rise of CO_2-concentration in the past for the major regions in the world. The contribution of Western-Europe and North-America amounts to about 40%; for Eastern Europe (including USSR) about 20%, and Japan/Oceania about 5%. For all these regions combustion of fossil fuels is the major cause. On the other hand, the relative contributions of Africa, Latin America and South/South East Asia (exceeding 30%) are for about 75% due to deforestation.

When the relative share of emissions is used to estimate the relative contribution (Krause *et al.*, 1989) to the greenhouse effect, the contribution of some regions will be overestimated and for some underestimated (Figure 3.5). Contributions of West European regions and North America are overestimated, because these regions have a relatively large part of their emissions in the last century, which are for the main part removed from the atmosphere by natural processes. However, for regions like East Europe, whose emission rate accelerated especially over the last decades, an emission accumulated approach would give an underestimation, mainly because a relative large part of the accumulated emissions over the last decades is still in the atmosphere. However, the differences between both approaches remain less then 10 percent.

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[6] As described in section 2.2, IMAGE has a simulation period between 1900 and 2100. For the 1800 version of IMAGE (simulation time between 1800 and 2100), the deforestation and terrestrial modules were set off. For the ocean model, the initial value in the surface layers were initialized at the 1800 -value given by Goudriaan and Ketner (1984).

[7] The deforestation and terrestrial biosphere module is also set off in the 1900 version to run the model with the regional external input parameter, the CO_2-emissions due to land use changes. This implies that also the CO_2-uptake by the terrestrial biosphere by negative biogeochemical feedbacks (den Elzen and Rotmans, 1991) is not simulated in this exercise, resulting in an unbalanced carbon budget over the historical period, and thus a simulated CO_2-concentration of 371 ppmv in 1990 (observed value is 354 ppmv). Also the fact that the carbon flux from land use changes in this study are higher than those of IMAGE (see section 3.2.3) cause an higher concentration level. This however does not affect the results of the relative contribution of each region.

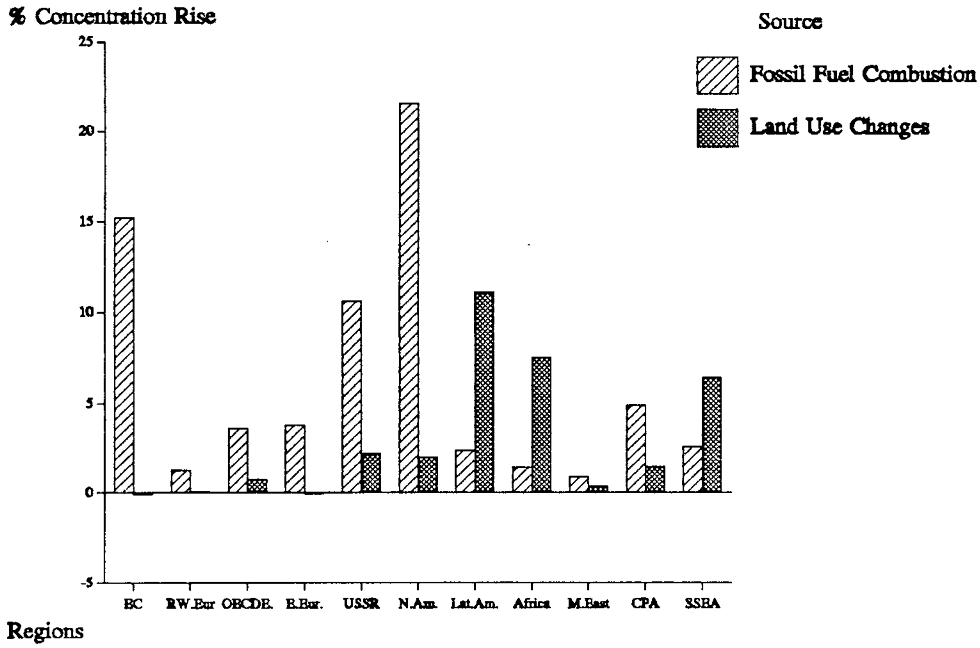

Figure 3.4: Relative regional contribution to the CO_2 concentration rise by fossil fuel combustion (incl. cement production) and land use changes.

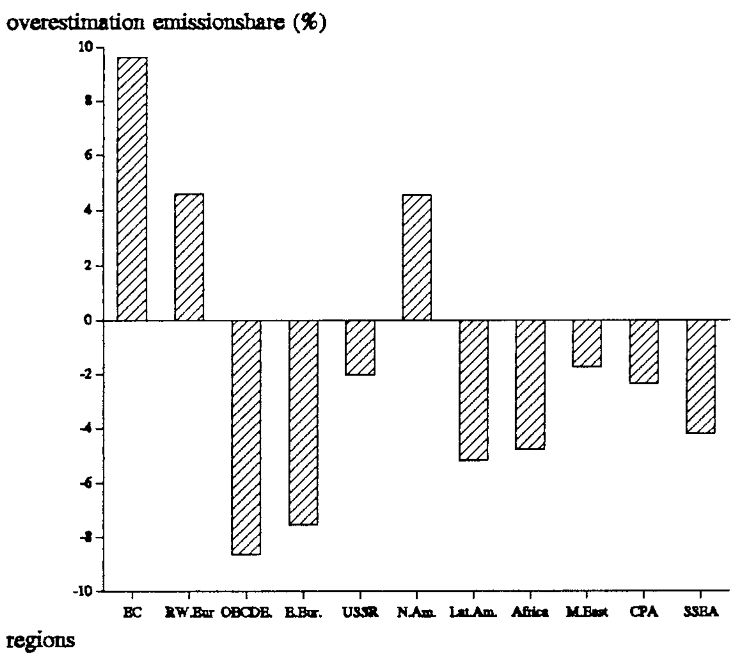

Figure 3.5: Overestimation when emission share is used relative to the contribution to the concentration rise.

3.4 Emission Debt

3.4.1 Introduction

In the past years there have been lengthy discussions about proposals for emission 'rights' of greenhouse gases for the future. Some have argued in favour of a global per-capita carbon budget; others have argued that the state of the economy should be reflected. Examples of these equity rules given in the literature are land area (Grubb, 1989), degree of efficiency (Grubb and Sebenius, 1991), the contrast between 'luxury' and 'necessary' emissions (Grubb and Sebenius, 1991), emissions per unit of GNP (Krause *et al.*, 1989; Grubb, 1989; Grubb and Sebenius, 1991) and emissions per capita (Krause *et al.*, 1989; Grubb, 1989; Fujii, 1990; Grubb and Sebenius, 1991).
The process of finding acceptable indicators as a base for allocation is getting momentum now, as part of the attempts to set up a global climate agreement. A consensus about such indicators and budgets will become more difficult to realize when measures for continued emission reductions are delayed.
We now introduce the term 'emission debt', trying to quantify the fact that some regions have emitted more in the past than they were allowed to, based on an equal share per capita. After Fujii (1990), we focus on a simple equity rule: *Every human being has an equal emission quota per year irrespective of both the regions he or she lives in and the generation he or she belongs to.* This approach enables us to see the problem more intuitively from the viewpoint of intergenerational and interregional equity and is also world-wide accepted. Besides that, this criterion can practically be worked out, population data[8] is available over the whole period 1800 till 1990, while for other criteria there is hardly any data in the past. Although this criterion favours the developing countries in which the population expand enormously, whereas those of the industrialized countries will be constant or even decline in the next century, thus giving the developing countries through their population growth more rights to emit carbon in future. This implies that in the international negotiations about emission rights, this point will certainly be addressed and could lead to an equal emission quota based on a constant future population, which is also being studied here.
Figure 3.6 shows that the global emission per capita is increased in the last 190 years, which is mainly caused by the increasing fossil fuel consumption. Emission per capita differs also between regions (Figure 3.7). In OECD and FCP regions emissions are for the main part caused by fossil fuel combustion, while in developing regions deforestation is the main source.

[8] The population data between 1800 and 1920 are based on Durand (1967). Over the period 1920 and 1990 the population data are obtained from the United Nations World Population Prospects (UN, 1966; UN, 1990). The future population is based on recent analysis of the World Bank (Bulatao *et al.*, 1990). Global population is estimated from 5.3 billion in 1990 to 11.3 billion in 2100, mainly by the growth in the developing countries (Appendix 5).

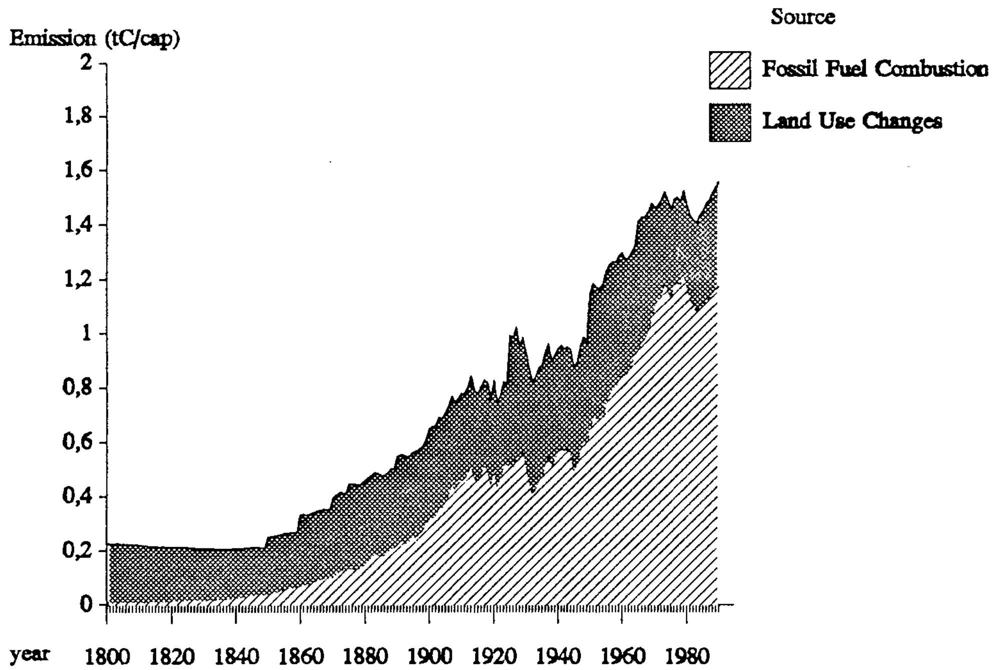

Figure 3.5: Global carbon emissions per capita for the period between 1800 and 1990. The increase is mainly caused by increasing fossil fuel combustion.

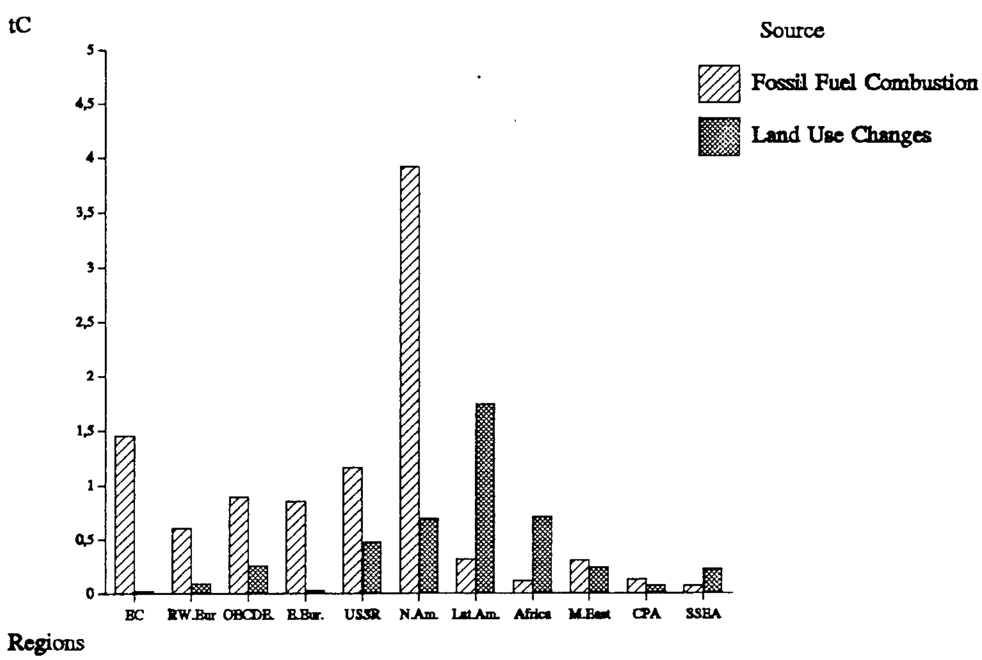

Figure 3.7: Average emission per capita for the period between 1800 and 1990. Regional differences excist in source and amount of emissions.

When we assume that every human being has an equal quota yearly and that human activities are constrained by reaching sustainable climate targets, we can define emission debt as the difference between historical emissions and an emission scenario based on equal emission quota per capita. In analytical terms, emission debt has the following relation,

$$ED(T,r) = \sum_{t=1800}^{T} EM(t,r) - Q_{cap} \cdot \sum_{t=1800}^{T} pop(t,r) \qquad \forall\ T,r \tag{3.6}$$

with:

ED(t,r)	= Emission Debt from region till year t (in GtC)
EM(t,r)	= Emission of carbon from region r in year t (in GtC/yr)
pop(t,r)	= population of region r in year t (in bil cap)
Q_{cap}	= emission quota per capita per year (in tC/cap*yr)

The breakeven value of Q_{cap} (Q_{cap}^*) is equal to the emission per capita yearly in the past leading to no emission debt in 1990. A region has an emission debt when its average emission per capita of the past (Figure 3.7) exceeds this Q_{cap}^*-value, otherwise it still has some credit to emit carbon in the future. The breakeven Q_{cap}^*-values for total global carbon emissions is 0.91 tC/cap*yr and 0.58 tC/cap*yr when only fossil fuel combustion is taken into consideration.
In this section we use two different approaches to estimate Q_{cap}, the equal emission quota per capita. The first approach is based on a scenario for the period between 1800 and 2100, defined by population multiplied by Q_{cap}. In the second approach Q_{cap} depends on a global carbon budget, which is the sum of the historical and future emissions which reach one of the sustainable climate targets. Because the CO_2 concentration depends on the distribution of emissions in time, Q_{cap} is different for the two approaches. The second approach will result in a higher Q_{cap} because the sum of emissions of a historical scenario followed by a decreasing future scenario is higher than an increasing emission path (dependent of population) to reach the same sustainable climate target, because historical emissions are for some part removed from the atmosphere through natural processes (Figure 3.8).

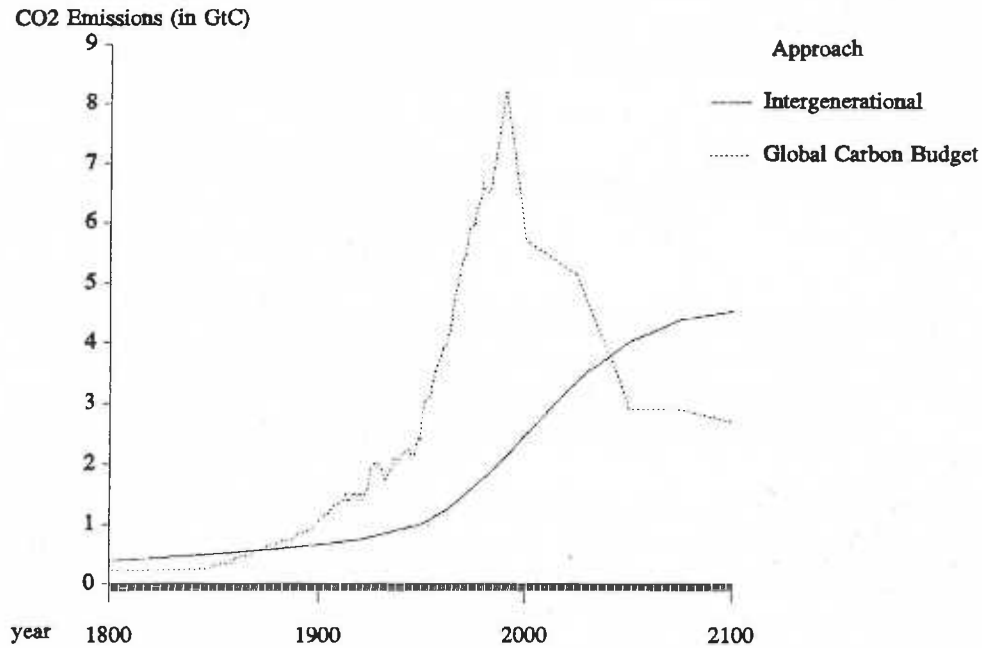

Figure 3.8: The emission scenarios of the budget approach and the intergenerational approach lead to the same concentration in 2100 but differs in the total emission flux between 1800 and 2100.

3.4.2 Intergenerational Approach

3.4.2.1 Introduction

Based on the equity rule, we define Q_{cap} as the amount of emission per capita yearly, leading to an emission path over the whole period 1800 till 2100, which is allowed to be emitted in the atmosphere in the past and in the future, on the condition that the CO_2-equivalent concentration does not exceed one of the three concentration targets as described in section 2.4.
We now describe two methods for calculating the Q_{cap}-values; an analytical approach and a dynamic modelling approach. The analytical approach is similar to the work of Fujii (1990). Here also the influence of the non-CO_2 gases is neglected and the target is set on a doubling of the pre-industrial CO_2 concentration value. In this study we compare our analytical results with these of Fujii (1990). In the dynamic modelling approach we use the integrated assessment model IMAGE for calculating the Q_{cap}-values for the three climate targets.

3.4.2.2 Methodology

<u>Analytical approach:</u>

In the analytical approach we calculate Q_{cap} based on the following simplified equation for the atmospheric CO_2-concentration (Rotmans, 1990):

$$pCO_2(t) = pCO_2(t-1) + atmcf \cdot af \cdot EM(t) \qquad (3.7)$$

with:

$pCO_2(t)$	= atmospheric CO_2 concentration at time t (ppmv)
atmcf	= factor that converts emissions of CO_2 into concentration; is 0.471 ppmv/GtC according to Brewer (1983)
af	= airborne fraction (fraction of the total CO_2 emissions from fossil fuels and land use changes that remains in the atmosphere), assumed to be constant
EM(t)	= fossil fuel combustion flux at time t (GtC)

Here we neglect the influence of the non-CO_2 gases. When we write emissions as Q_{cap} multiplied by population, Q_{cap} can be calculated using the equation:

$$Q_{cap} = \frac{pCO_2(2100) - pCO_2(iy)}{\sum_{t=1800}^{2100} atmcf \cdot af \cdot wpop(t)} \qquad (3.8)$$

with:

$pCO_2(iy)$	= initial atmospheric CO_2 concentration (ppmv)
wpop(t)	= world population at time t

Fujii (1990) adopted a similar approach for calculating the Q_{cap}-value, although Fujii used a discount factor $(1- 1/T_0)^{2100-t}$ in equation 3.7 and equation 3.8 (denominator) for

discounting the historical emissions of carbon. This factor represents in a simplified way the effect of the long-term oceanic uptake, in which Fujii adopted a time constant T_0 of 300 years based on the time of the largest amplitude exponential of Maier-Reimer and Hasselman (1987) linear response function. In reality the interactions between ocean, terrestrial biosphere and atmosphere follow a complex dynamic process, which can not be described by a constant airborne fraction factor and a discount factor. The airborne fraction is time-dependent, because of the dependency on the atmospheric CO_2 concentration and the CO_2-concentration in the upper oceanic layer. Fujii assumes an airborne fraction of 0.42, which is low compared to the range (0.50-0.58) given by Perry (1984) and Trabalka *et al.* (1985), the historical value of 0.5 given by the IPCC (1990) and the averaged simulated value of 0.6 from IMAGE over the period 1900 till 1990.
These differences can be explained by analyzing the carbon budget over the 1980s (1980-1989). According to the IPCC (1990) over this period the atmospheric sink equals to 3.4 $\pm$ 0.2 GtC/yr, while the total source amounts 7.0 $\pm$ 1.5 GtC/yr (5.4 $\pm$ 0.5 GtC/yr from fossil fuel burning and 1.6 $\pm$ 1.0 GtC/yr from land use changes). The emissions from the land use changes is the only carbon flux which differs among the literature sources. Fujii (1990) based the CO_2-flux on Houghton *et al.* (1983), resulting in a flux at the maximum boundary of the uncertainty range given by the IPCC (1990), 2.6 GtC/yr. However, the CO_2-flux due to land-use changes according to Rotmans and Swart (1991) is rather low, 1.3 GtC/yr. These differences explain the low airborne fraction given by Fujii (1990) and the high value of IMAGE. Lower estimates of this airborne fraction lead to less carbon being stored in the atmosphere due to the CO_2 emissions, thus higher values of Q_{cap}, as illustrated in Table 3.4. for the airborne fractions given by Fujii, IPCC (1990) and IMAGE. The resulting absolute emission debt on world-scale in 1990 varies from a credit of 50 GtC of Fujii to a debt of 80 GtC according to IMAGE.
The difference between the two periods is caused by the low per capita emissions (0.36 tC/cap*yr) in the last century, which cause a decline in Q_{cap} when this century is neglected. However, the difference is small because of the small population size of the last century compared with population prospects.

Table 3.4 Q_{cap} (in tC/cap*yr) for different values of the parameters (in tons) and with $pCO_2(2100)$ is 560 ppmv.

period / airborne fraction	1800 - 2100	1900 - 2100
Fujii (1991) (af = 0.42)	1.02	1.05
IPCC (1990) (af = 0.50)	0.85	0.88
IMAGE (af = 0.60)	0.71	0.74

Discounting historical emissions leads to higher estimates for the Q_{cap}-value, 1.31 for Fujii (1990), corresponding with an emission credit 150 GtC. Fujii calculates under the same condition a Q_{cap} value of 1.37 ton carbon per capita yearly, which is somewhat higher than our estimate, because our future population projections were based on Bulatao *et al.* (1990) which are somewhat higher than the population projections of Zachariah and Vu (1988) used by Fujii.

Dynamic Modelling Approach:

Because the previous analytical method was only based on the greenhouse gas CO_2, we could not calculate the emission debt coupled to the climate targets, as defined in terms of CO_2-equivalent concentration. In the dynamic modelling approach we make use of the greenhouse model IMAGE to calculate the (regional) emission debt coupled to a climate target (expressed in CO_2-equivalent concentration level in 2100) based on the equity rule. Because the climate targets are coupled to an emission scenario, we choose this target related scenario for the non-CO_2 gases. We formulate for the emissions of CO_2 (including deforestation and fossil fuel combustion) an equitable emission scenario (Q_{cap} times population[9]), and then iteratively derive after several simulation runs with IMAGE the Q_{cap}-value belonging to each climate target. In this experiment we turned off the deforestation and terrestrial biosphere module in IMAGE, thus no uptake of the CO_2 emissions by the terrestrial biosphere took place, only by the oceans. This results in somewhat high estimates for the CO_2 concentration, as the negative biogeochemical feedbacks, like CO_2 fertilization effect are ignored in the model. The results of the Q_{cap}-values under the three climate targets are shown in Table 3.5. The uncertainty range depends on the assumptions of the non-CO_2 gases, the lower bound represents the Business-as-Usual scenario and the higher bound the reference scenario.
UN population prospects (UNPFA, 1991), which ends in 2025, presents high and low scenarios, which have 30% higher and lower growth rates than the middle scenario. Using these scenarios Q_{cap} changed with 10%. Thus a 30% higher growth rate results in a 10% lower Q_{cap}.
In comparison with the previous method, we also calculate the Q_{cap}-value for the dynamic approach under the doubling CO_2 concentration target. This results in a Q_{cap} of 0.78 (1800-2100) and 0.83 (1900-2100) for the two periods, which is within the range of the estimates based on airborne fractions of IPCC (1990) and IMAGE. The results show that discounting historical emissions as used by Fujii (1990) leads to a Q_{cap} which is almost two times higher than using IMAGE and therefore it over-estimates the ocean uptake.

The Q_{cap} for fossil fuel CO_2 emissions alone can be calculated analogous. For this experiment we can run the simulation model IMAGE including the deforestation and terrestrial biosphere modules. The resulting Q_{cap}-values (Table 3.5) are higher than estimates with land use changes because of the negative biogeochemical feedbacks. Also the historical emission path of deforestation (removed for a part from the atmosphere) and the future afforestation cause a rise of Q_{cap}-values. However, when deforestation remains uncontrolled the high emission fluxes cause a decline of Q_{cap} (lowerbound Q_{cap}).

[9] Emissions of CO_2 and non-CO_2 gases are now independent in the 'ethical' scenario.

Table 3.5. Q_{cap} values (in tC/cap*yr) under the three climate targets for both fossil fuel combustion and land use changes (first two rows), and fossil fuel combustion only. The lowerbound of the range is derived with the Business-as-Usual scenario for non-CO_2 gases and the upperbound with the target related scenario.

Target \ Period	1800 - 2100	1900 - 2100	1900 - 2100 (Fossil Fuel only)
Concentration Stabilization (560 ppmv)	(0.22, 0.50)	(0.24, 0.54)	(0.24, 0.58)
Absolute Temperature (530 ppmv)	(0.14, 0.40)	(0.17, 0.44)	(0.14, 0.51)
Relative Temperature (475 ppmv)	(0.06, 0.33)	(0.08, 0.37)	(0.04, 0.38)

When we restrict the concentration to doubling of the CO_2 equivalent concentration in 2030 (Business-as-Usual), 2060 (Low Emissions) and 2090 (Control Policies) with corresponding scenarios for the other trace gases, this results in Q_{cap} of 0.86 tC/cap*yr for the 2030 case, 0.56 tC/cap*yr for the 2060 case and 0.50 tC/cap*yr for the 2090 case (Table 3.6). These values are significant lower than present emissions per capita (1.5 tC/cap), also for the Business-as-Usual scenario. The conclusion holds when only fossil fuel combustion is taken into consideration, although for the Business-as-Usual case there is a global carbon credit while the Q_{cap} is larger than the breakeven value (0.58).

Table 3.6: Q_{cap} (in tC/cap*yr) values under three IPCC doubling cases for both fossil fuel combustion and land use changes, first two rows, and fossil fuel combustion only.

Target\Period	1800 -	1900 -	1900 - (Fossil Fuel only)
Business as Usual (2030)	0.86	0.97	0.91
Low Emissions (2060)	0.56	0.58	0.57
Control Policies (2090)	0.50	0.54	0.55

3.4.2.3 Emission Debt

The Q_{cap}-values derived with the dynamic modelling approach are now used to estimate regional and global debts. The emission debt world-wide is under the concentration stabilization target 155 GtC (Q_{cap}=0.50), the absolute temperature target 193 GtC (Q_{cap}=0.40) and the relative temperature target 220 GtC (Q_{cap}=0.33).
The global emission debt in time is depicted in Figure 3.8 for different Q_{cap} values. A high Q_{cap}-value results in a credit for the first part of the period, which means that in this period the population emitted less then was allowed on the equity rule. The ranges of debts using two targets (concentration stabilization and relative temperature) have a overlap. The uncertainty range of the global emission debt in 1990 (155, 323 GtC) is for the main part caused by differences in scenarios for other trace gases (Business-as-Usual versus target related scenarios).
All regions have increasing emission debts (or decreasing emission credits) for the last decades (Figure 3.10). The emission debt of North America has over the whole period the largest rate. In the beginning caused by large deforestation rates, followed by large fluxes by fossil fuel combustion. CPA and South/South East Asia still have an emission credit in 1990.
In Figure 3.11, the regional emission debts in 1990 are given for different Q_{cap}-values. The first two bars depict debt using the concentration stabilization and the relative temperature targets. The last bar shows the debt using the relative temperature target with a Business-as-Usual scenario for non-CO_2 trace gases. The ranges of uncertainty of the regional debts are relatively small for most regions. However, for Central Planned Asia and South/ Southeast Asia, the differences are large, which is caused by the large population size.
When we divide Q_{cap} proportional to historical emissions by fossil fuel combustion and land use changes (Q_{cap} = 0.40 = 0.25 (fossil fuel) +0.15 (land use changes)) a regional fossil fuel debt and land use change debt can be derived. Emission debt in industrialized regions are for the main part caused by fossil fuel combustion (Figure 3.12), while Latin America has the largest deforestation debt per capita. The differences in stage of economic development cause differences in the amount and sources of emission debt.
When only fossil fuel combustion is used to estimate Q_{cap}, the fossil fuel emission debt is smaller than when Q_{cap} of both sources is divided (Figure 3.12). The resulting world-wide emission debt of fossil fuel combustion is under the concentration stabilization target 1 GtC, the absolute temperature target 25 GtC and the relative temperature target 75 GtC. When deforestation and emissions of other greenhouse gases remain uncontrolled the emission debt increases to 205 GtC for the relative temperature target.

The Q_{cap} values which corresponds with the doubling years of the IPCC scenarios results in a global emission debt for the period 1800 till 1990 of 18 GtC for the Business-as-Usual scenario, 132 GtC for the Low Emission scenario and 155 GtC for the Control Policies scenario. When only fossil fuel combustion is taken into consideration, then for the period 1900 till 1990 their is a global emission credit of 127 GtC for doubling the CO_2 concentration in 2030, while a debt remains of 2 GtC for doubling in 2060 and 10 GtC in 2090.

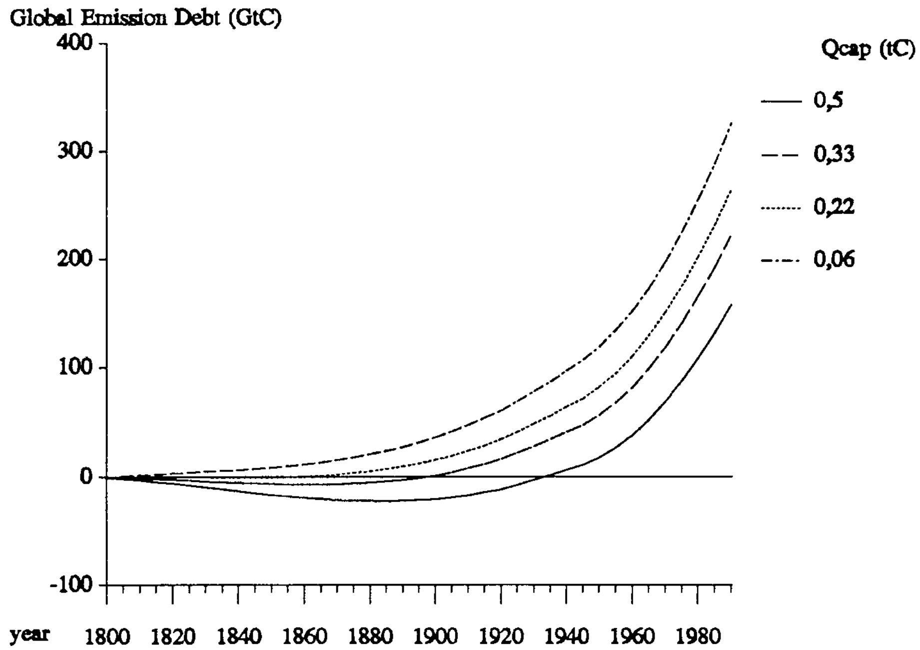

Figure 3.9: Global emission debt for different Q_{cap}-values.

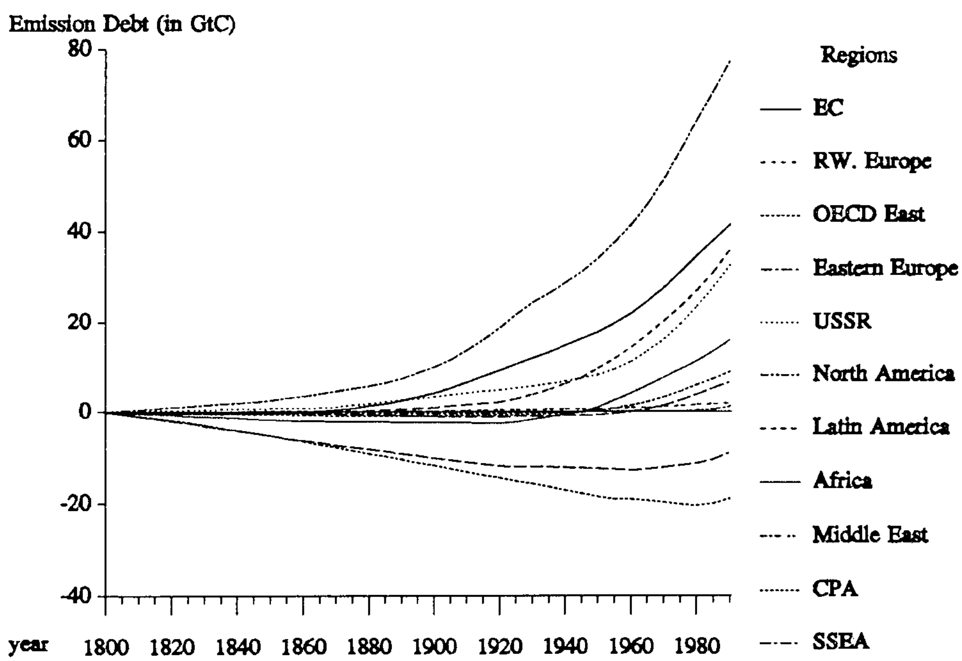

Figure 3.10: Regional emission debt between 1800 and 1990 using a Q_{cap}-value of 0.40 (absolute temperature target).

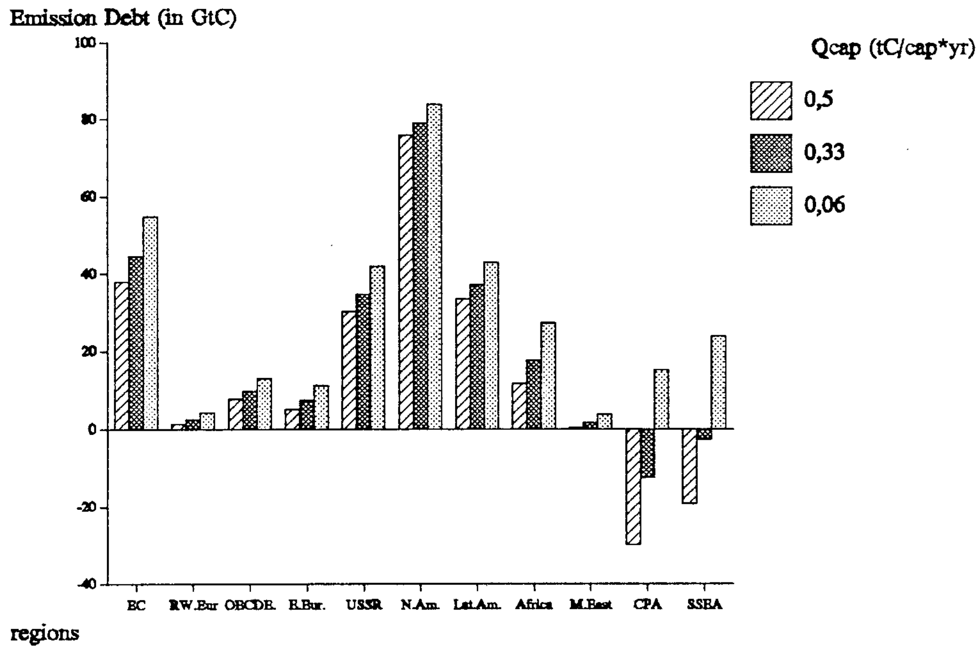

Figure 3.11: Regional Emission debt in 1990 for different Q_{cap}-values.

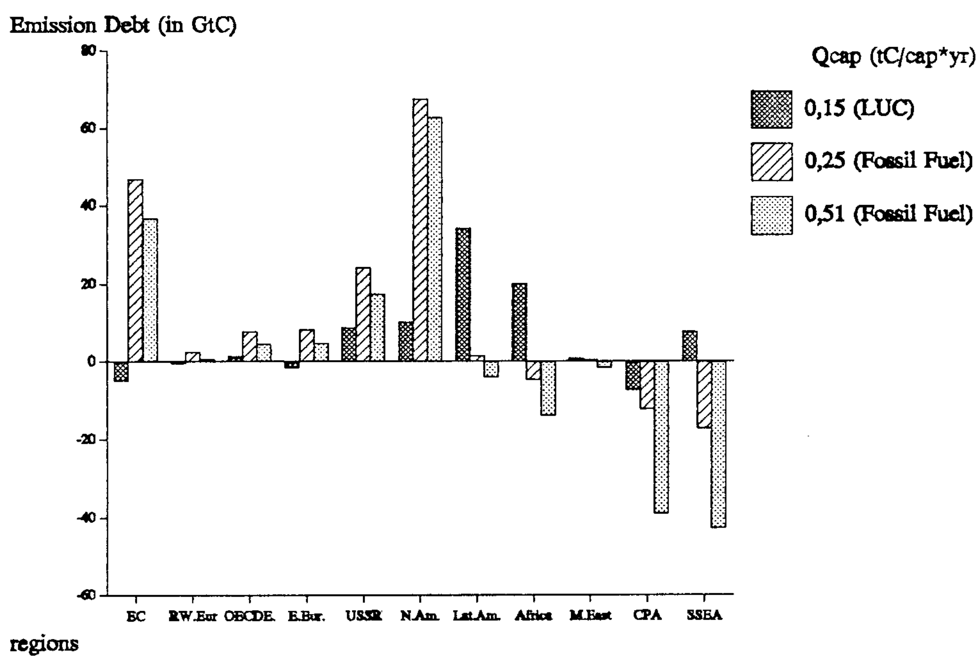

Figure 3.12: Regional deforestation (first bar) and fossil (second bar) emission debt by dividing Q_{cap} proportional to historical contibution. Third bar depict fossil debt alone.

3.4.3 Global Carbon Budget Approach

3.4.3.1 Introduction

One approach to the problem of 'emission debt' is to consider the atmosphere as a sink which can absorb over the period 1800-2100 only a limited amount of greenhouse gases, expressed in CO_2-equivalent concentration is not to be exceeded at the end of the period (den Elzen *et al.*, 1992). This level of CO_2-equivalent concentration is coupled to climate targets as defined in section 2.4. (560 ppmv for *concentration stabilization* target, 530 ppmv for *absolute temperature* target and 475 ppmv for *relative temperature* target). For the period 1990 till 2100 there is a limited amount left to be emitted. We call this the remaining global carbon budget.

3.4.3.2 Methodology

We have calculated the global carbon budget under the three targets by using emission scenarios as described in section 2.4. The accumulated carbon budget (CO_2 emissions from fossil fuel combustion and land use changes) over the period 1800 till 2100 amounts about 890 GtC under the concentration stabilization target, about 780 GtC under the absolute temperature target and about 670 GtC under the relative temperature target.
In the past (1800-1990) 346 GtC (fossil fuel combustion and deforestation) has been emitted, implying 39% for concentration stabilization target, 44% for the absolute temperature target and 52% for the relative temperature target. Thus, the remaining global carbon budget for the three targets amounts respectively to 545 GtC[10], 440 GtC and 320 GtC. This budget includes both fossil and biotic emissions of carbon (energy, cement and deforestation).
If the world community does not follow such an emission path for CO_2, but instead the continued growth of the IPCC Business-as-Usual scenario, the accumulated carbon emissions would be 1930 GtC. However, such a scenario does not meet any climate target. To realize this, a precipitous decline in emissions is required to meet the climate target after the year 2030, 2020 and 2010 for respectively the concentration stabilization target, absolute temperature target and the relative temperature target. The remaining global carbon budget would, with such an emission time-path, be decreased to 520 GtC (-5%) for the concentration stabilization target, 420 GtC (-4%) for the absolute temperature target and 310 GtC (-3%) for the relative temperature target. Two remarks are in place here. First, in the calculations the targets expressed in CO_2-equivalent concentration are exceeded during a part of the period 1990 till 2100, although at the end-point 2100 the CO_2-equivalent constraint is achieved. Secondly, here it was assumed that the emissions of other non-CO_2 greenhouse gases are following the target related scenario after break point time. If they remain uncontrolled and still follow the Business-as-Usual scenario after this

[10] Krause *et al.* (1989) derived a global carbon budget of 200 - 300 GtC using the concentration stabilization target. They used a CO_2 concentration limit (after substracting the CO_2 equivalent concentrations of other greengouse gases) to estimate the budget. Our simulation shows lower CO_2 concentrations than for the same emission path (den Elzen en Rotmans, 1991), which is one factor which explain the difference. An other factor which reduce their carbon budget relative to our results is the high concentration values (110 - 180 ppmv) substracted from the doubling target compaired with IMAGE results (120 - 130 ppmv).

break time, then the global carbon budget for this scenario would vanish. The uncontrolled emissions of other tracegases till the breakpoint is also the main cause of the decrease of the global budget. Thus, the role of non-CO_2-gases is not to be neglected in any negotiation about future budgets.
The maximum remaining global carbon budget (see chapter 5) is 590 GtC (+8%) for the concentration stabilization target, 510 GtC (+16%) for the absolute temperature target and 380 GtC (+19%) for the relative temperature target.
After given ranges of the remaining global carbon budgets, we can define Q_{cap} as the average emission per capita over the period between 1800 and 2100,

$$Q_{cap} = \frac{\sum_{r} \sum_{t=1800}^{1990} EM(t,r) + \sum_{r} \sum_{t=1991}^{2100} EM_{scen}(t,r)}{\sum_{t=1800}^{2100} wpop(t)} \tag{3.9}$$

3.4.3.3 Allocation of Emissions in the Future

The first question is how to evaluate past emissions with respect to the global budget. Has mankind emitted more carbon than it should have? One way to approach this question is to calculate the per-capita emission budget which over the period 1800-2100 would exactly consume the overall budget, using past, present and projected world population.
For the IPCC Accelerated Policies scenario, every human being in this period would (have) be(en) allowed to emit 0.56 tC per year. Using this approach it is found that the global budget for the past 190 years has been exceeded by 130 GtC. One may interpret this result in terms of emission debt: past global populations were allowed to consume 27% of the budget whereas they actually emitted 44%. In other words: our ancestors have reduced emission rights for our descendants. The global debt can be divided into 118 GtC from OECD regions (where 75 GtC of North America), 33 GtC from FCP regions and a credit of 19 GtC for developing regions. For the concentration stabilization and the relative temperature target, the global historical budget has exceeded by 100 GtC and 165 GtC respectively and the equity per-capita amounts 0.64 and 0.48 tC per year respectively.
The different scenarios which lead to the same climate target cause a range within 10% of Q_{cap}. When low and high population prospects are used (UNPFA, 1991), it will cause a 15% difference of Q_{cap} with a change of the growth-rate of 30%.
The next question is how the remaining global carbon budget could be distributed over the different regions and over time, taking into account past and present emissions of carbon dioxide. Note that the contribution from past emissions is not proportional to cumulative emissions since 1800, since much of the emitted carbon have already been removed from the atmosphere through natural processes. The remaining regional carbon emissions ($BUD_{left}(t,r)$) can be estimated by subtracting historical emissions from the regional budget over the period 1800 till 2100 (3.10).

$$BUD_{left}(r) = Q_{cap} \cdot \sum_{t=1800}^{2100} pop(t,r) - \sum_{t=1800}^{1990} EM(t,r) \tag{3.10}$$

As a reference case, we first study the regional emission debt under the absolute temperature target. Figure 3.13 shows the results of this approach for the reference case based upon the carbon budget including fossil fuel combustion and land use changes. The first bar represents the current emission on a per-capita basis (world average: 1.5 tC/cap*yr). When the global budget is distributed proportional to a constant population size, every human being is allowed to emit 0.75 tC per year (second bar), which is an average reduction of 50 percent of present emission. When population prospects are used, the average quota per capita per year decreased to 0.44 tC (third bar). The developed and most of developing regions get significant less than present emission levels. This future emission allowance is smaller than 0.56 tC (Q_{cap}), caused by high emission levels per capita in the past.
When emission debt is used to allocate emission permits (Bud_{left}), future budgets further decline in developed regions down to negative values for North America. In most developing regions budgets increased, except in Latin America.
The regional budgets left per capita after clearing debt under future population growth for the two other climate targets are also depicted in the last bars, which shows a small range relative to the decline of budgets due to population growth.

Figure 3.14 shows similar results but excludes carbon emissions from land use changes[11]. The average present emission per capita of 1.2 tC has to be reduced to 0.79 tC/yr when the global budget (excluding deforestation and afforestation) is distributed proportional to constant population size (second bar). Anticipated fast population growth reduces this budget to 0.46 tC per capita per year (third bar), which is lower than Q_{cap} (=0.49 tC/cap*yr). This is for the OECD, the USSR, Eastern Europe and the Middle East significant lower than the present rates. Accounting for past debts and credits gives an increase or a same emission level for the developing world, whereas North America ends up with a negative per-capita allowance. Note that the increase for the poor regions is a minor one if compared with present per-capita emission rates. The regional budgets left under future population growth after clearing debt for the two other climate targets are also depicted in the last bars.

[11] The global budget is now about 30 GtC higher because in the target-scenarios there is a net uptake due to afforestation.

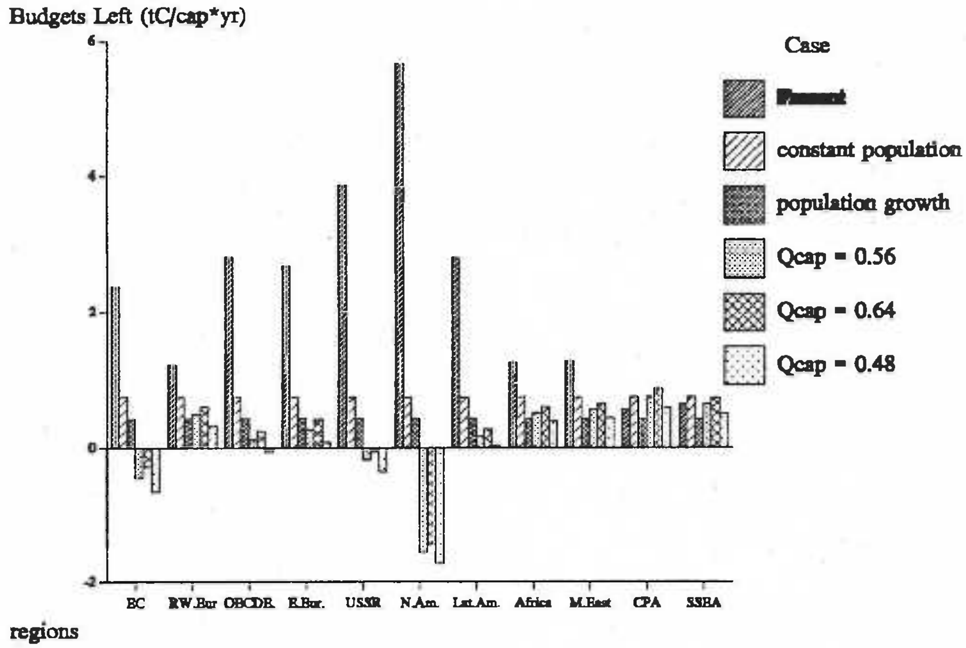

Figure 3.13: First bar: present emission per capita; Second bar: budget per constant population; Third bar: budget per growing population; while in the last three bars debt is cleared.

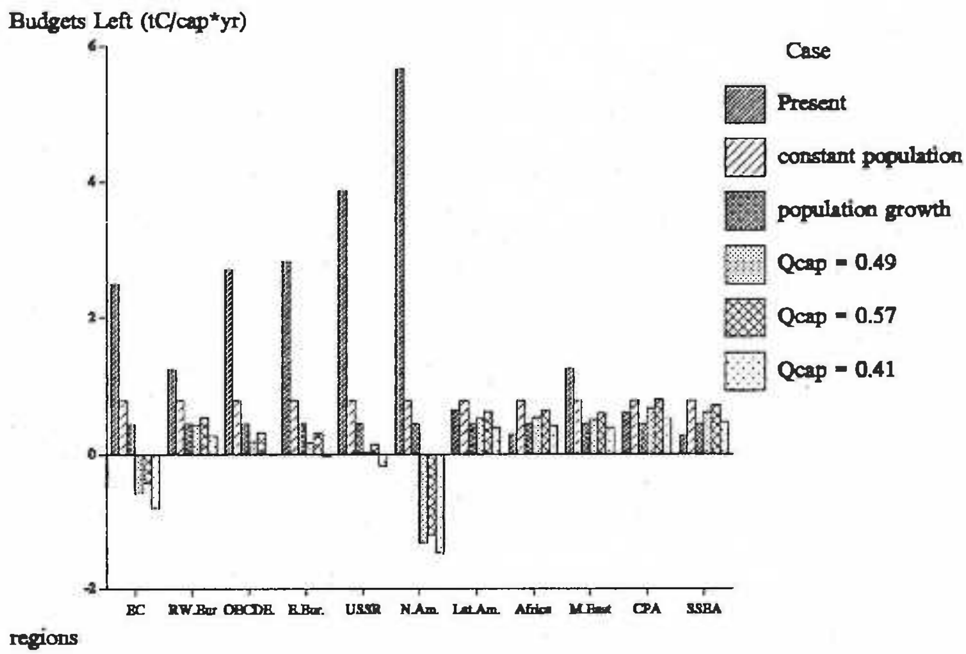

Figure 3.14: First bar: present emissions by fossil fuel combustion. Second and third bars: budgets per constant and growing population, while in the last bars debt is cleared.

3.5 Historical Emissions versus Financial External Debt

We have seen that substantial differences occur between the regional contributions to the CO_2 concentration rise. There are also large differences between regional emission debts, also in the underlying sources: deforestation and fossil fuel combustion. Figure 3.15 shows that also large differences exist in the financial external debts[12] (expressed as percentage of GNP) between the regions. In this section we discuss the statistical relation between the historical CO_2 emissions and the financial external debt.

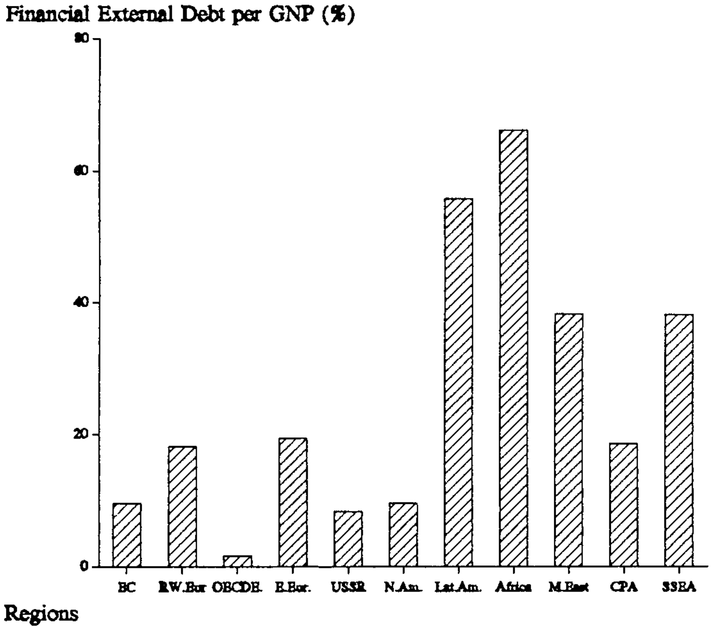

Figure 3.15: External debt as percentage of GNP for different regions at the end of the eighties.

Figure 3.16 clearly shows that there is a positive relation between welfare, measured by GNP per capita and the relative contribution to the CO_2 concentration rise by fossil fuel combustion per capita. We performed a regression analysis over 11 regions between GNP per capita and respectively present emission, historical relative contribution to the CO_2 concentration rise and emission debt, all three for fossil fuel combustion and per capita. In Table 3.7 the values of the estimated coefficients of linear relations between the indicators are given. The correlation with the relative contribution is relative high, while it is somewhat lower with present emissions and emission debt. These relations show that present welfare in industrialized countries rests on large CO_2 emissions in the past.

[12] External debt data for the most countries are obtained from OECD statistics (OECD, 1990). Most of the developed countries are excluded from World Debt tables (World Bank, 1990a; 1990b), and external debt is also excluded for most of the developed countries from the World tables (World Bank, 1989). However a rough estimate of external debt for those developed regions is made by use of IMF (1991) and EIU (1987) data. From the IMF (1991) data, foreign govermental debt or debt in foreign currency is used and when no IMF data were available, public or governmental foreign debt of the EIU (1987) data is used. GNP data are obtained from FAO (1990).

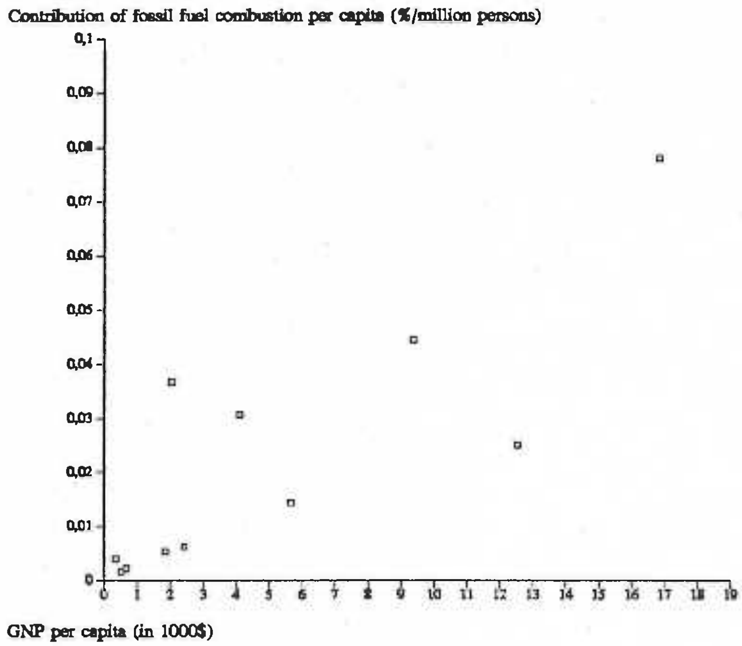

Figure 3.16: Relation between relative contribution by fossil fuel combustion to the concentration rise per capita versus GNP per capita for the 11 regions.

Table 3.7: The estimated coefficients of relations between GNP and fossil fuel combustion, with:

GNP/POP	EM_{ff}/POP	R^2
coefficient t-value[13]	253.5 (6.1)	0.59
GNP/POP	RCC_{ff}/POP	
coefficient t-value	210 (7.0)	0.67
GNP/POP	ED_{ff}/POP	
coefficient t-value	0.07 (6.4)	0.61

GNP = Gross National Product (in billion $)
POP = Population (in million persons)
EM_{ff} = CO_2 emissions in 1990 by fossil fuel combustion (in GtC)
RCC_{ff} = Relative contribution in the concentration rise by fossil fuel burning (%)
ED_{ff} = Emission Debt (part caused by fossil fuel combustion) (in million tC)

[13] When a significance-level of 10 percent is to be reached, the absolute value of the t-value has to be larger than 1.65 for a statistical significant relation. This value is 1.96 for 5 percent uncertainty and 2.58 for 1 percent uncertainty.

Figure 3.17 shows that there is a positive relationship between financial external debt as percentage of GNP and the relative contribution to the CO_2 concentration rise by land use changes per unit of GNP. Estimating a linear relation between those indicators results in a significant correlation (Table 3.8). The significance increase slightly when we use present emissions by land use changes, and it decrease somewhat when we use emission debt by land use changes (Table 3.8). This exercise show that in regions with a high financial external debt there is also large deforestation.

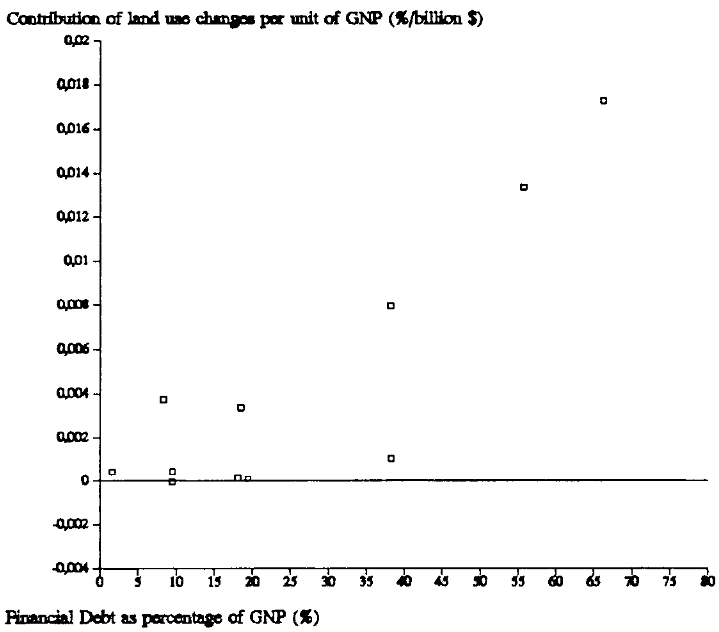

Figure 3.17: Relation between external debt as % of GNP and the relative contribution to the CO_2 concentration rise by land use changes per unit of GNP for the 11 regions.

Table 3.8: The estimated coefficients of relations between financial external debt and land use changes, with:

FED/GNP	constant	EM_{luc}/GNP	R^2
coefficient t-value	16.2 (1.6)	34068 (5.9)	0.79
FED/GNP	constant	RCC_{luc}/GNP	
coefficient t-value	12.4 (1.2)	3066 (5.4)	0.77
FED/GNP	constant	ED_{luc}/GNP	
coefficient t-value	16.7 (1.2)	1.1 (3.7)	0.60

FED = Financial External Debt (in billion $)
EM_{luc} = CO_2 emissions in 1990 by land use changes (in GtC)
RCC_{luc} = Relative contribution in the concentration rise by land use changes (%)
ED_{luc} = Emission Debt (part caused by land use changes) (in million tC)

When we involve fossil fuel combustion, the statistical relations, which explains financial external debt, becomes more significant (Table 3.9). The financial debt as percentage of GNP has a negative relation with fossil fuel combustion and a positive relation with land use changes. The relation with the largest statistical correlation is given in equation (3.11).

$$\frac{FED}{GNP} = 19.0 - 1065 \cdot \frac{RCC_{ff}}{GNP} + 2949 \cdot \frac{RCC_{luc}}{GNP} \tag{3.11}$$

This relation could be explained as follows: Emissions from deforestation result from the early development of agricultural economies. In a following phase of industrialization and rapid growth of the per capita income levels, emissions related to the combustion of fossil fuel generally rapidly surpass these biotic emissions. Industrialized countries have reached a high level of welfare and have a low financial debt as percentage of GNP. The high financial debts and deforestation rates in Africa, Latin America and South/Southeast Asia reflects their present predicament: the squandering of their forest has become instrumental to the development of their economies and to feed their growing population. To put it differently: To relieve financial debts to the industrial regions, environmental debts are build up by exporting wood and agricultural products to the rich regions.

Table 3.9: The estimated coefficients of relations between financial external debt and fossil fuel combustion and land use changes.

FED/GNP	constant	EM_{ff}/GNP	EM_{luc}/GNP	R^2
coefficient t-value	14.9 (1.4)	1684 (0.3)	34575 (5.4)	0.79
FED/GNP	constant	RCC_{ff}/GNP	RCC_{luc}/GNP	
coefficient t-value	19.0 (1.9)	-1065 (-1.7)	2949 (5.7)	0.83
FED/GNP	constant	ED_{ff}/GNP	ED_{luc}/GNP	
coefficient t-value	19.1 (1.9)	-0.5 (-2.6)	1.2 (5.1)	0.78

3.6 Discussion

Analyzing past carbon emissions from fossil fuel use, cement manufacturing and deforestation indicates that present wealth in the industrialized countries is at the cost of large emissions in the past. The relative contribution of Western Europe and North America to past CO_2-concentration rise is about 40%, almost completely due to fossil fuel combustion. The contribution from Africa, Latin America and South/Southeast Asia, exceeding 30%, is for about 75% due to deforestation.
This clearly show the inequity between the developed and developing world, which we try to quantify via the concept of emission debt. We define emission debt as the difference between historical emissions and an amount of emissions based on a per capita emission quota (= every human being has an equal emission quota per year irrespective of both the region he or she lives in and the generation he or she belongs to). We used two different methods to estimate the regional emission debts:
- The intergenerational approach: If mankind has faced the allocation problem in 1800, each person living between 1800 and 2100 would have an allowance of 0.4 ton C yearly to meet the *absolute temperature target.* This result in an emission debt in 1990 of 190 GtC, mainly caused by industrial regions.
- The global carbon budget approach: We consider the atmosphere as a sink which can absorb over the period 1991 till 2100 only a limited amount of carbon to meet a climate target. The total global carbon budget is now this limited amount of carbon plus historical emissions. Every human being has the right to emit 0.56 ton C yearly of this global carbon budget, however, we have emitted in the past about an average value of 0.91 ton C per capita per year. The resulting emission debt is 130 GtC in 1990. Allocating the remaining global carbon budget, which takes account of past emissions, increased the budgets of developing regions in contrary to industrial regions, where even North America and the European Community ends up with negative budgets. Anticipated population growth reduces the average per-capita budget over the next 110 years with some 45% relative to a constant population size.

Effective preventive and adaptive response to climate change requires a concerted global effort. Present welfare in industrialized regions is obtained by large use of fossil fuels, while the developing regions squander their forest to relieve their financial debts. The industrialized countries have so far caused the major part of the problem and thus should take prime responsibility in responding, and supporting the developing countries to contribute their share. Therefore, the international policy discussion understandably adds the economic north-south issues to the search for technical options.

4 An Optimization Method to Allocate Carbon Emissions

4.1 Introduction

Investigating the consequences of an environmental policy may be viewed as an optimization problem in the following sense. Policies to reduce carbon emissions by fossil fuel combustion are subjected to several constraints. On the one hand a feasible environmental policy should minimize environmental damage on the society and ecosystems, and on the other hand the socio-economic consequences, such as cost should be minimized. Not only an environmental strategy should aim at an equitable share of the resources between the developing and industrialized countries, also intergenerational equity should be taken into account.

In this section we present an optimization method for socio-economic optimal allocating reductions of CO_2 emissions by fossil fuel combustion to regions in time under the constraint of reaching climate targets. The objective function in this optimization problem describes the social and economic consequences of a climate strategy. Since reliable assessments of cost and benefits of policies, which are necessary to quantify the objective functions, are still not available, the method here is used for rough estimates for those functions. The constraints are related with economics and environment. The environmental constraint relates to the target condition, whereas the economic constraint relates to the absolute emission reduction, as well as to the reduction rate. The optimization problem is formulated as a global optimization problem, which is only numerically solvable, because the environmental constraint can only be solved by a simulation run with IMAGE and because of many non-linearities, in the objective function as well as in the constraint functions.

The formulation of the optimization problem and the developed method to solve it are discussed in 4.2. Rough estimates for objective functions of the optimization problem are given in section 4.3. Section 4.4 presents some possible exercises which could be done with global emission allocation.

4.2 Methodology of the Optimization Problem

4.2.1 Formulation of the Problem

The time period of our interest is from 1990 till 2100. Let $x_{t,r}$ be the CO_2 emissions of region r (r = 1, .. ,11) in the year t (t = 1990, ... , 2100). Let $\mathbf{X} = [x_{t,r}]_{t=1990}^{2100}{}_{,r=1}^{11}$ be a matrix which characterizes the regional CO_2 emissions. For simplicity, emissions are assumed to be change linearly over certain time intervals on the time period of interest. In this study the following time intervals are used: $[T_0,T_1]$, ... , $[T_4,T_5]$, $T_0 = 1990$, $T_1 = 2000$, $T_2 = 2025$, $T_3 = 2050$, $T_4 = 2075$, $T_5 = 2100$. The regional emission path is denoted by $\mathbf{x}_r$ for region r. $\mathbf{X}$ can be written by $\{ x_{1,1}, x_{1,2}, .. , x_{1,11}, .. , x_{i,1}, .. , x_{i,11}, .. , x_{5,1}, .. ,x_{5,11} \}$, with $x_{i,r}$ the CO_2 emission at region r at time point T_i. The choice of $\mathbf{X} = [x_{i,r}]_{i=1}^{5}{}_{,r=1}^{11}$ together with the known value of the initial emissions $x_0 = [z_r]_{r=1}^{11}$ at time 1990, determines emission matrix $\mathbf{X}$ and thus a strategy. From now on we would like to consider $x_{i,r}$'s as the decision variables.

The problem of an optimal allocation of carbon emissions by fossil fuel combustion to regions in time is now formulated as an optimizing problem. (Note that problems of minimizing f($\mathbf{X}$) and maximizing -f($\mathbf{X}$) are equivalent)

$$\min_{X} \; f(X)$$

subject to

$$\begin{array}{llll} (a) & g_j(X) \leq 0 & \forall\, j & \qquad (4.1) \\ (b) & h_k(X,c(X)) \leq 0 & \forall\, k & \end{array}$$

$$\text{with } x_{i,r} \geq 0 \qquad \forall\, i,r$$

The policies are valued by an objective function ($f:\mathbf{R}^n \rightarrow \mathbf{R}$) which is assumed to be a continuous real valued function. Such a function deals with the social and economic consequences of some policy $\mathbf{X}$. Examples of these functions are cost and utility functions, which are discussed in section 4.3. In this problem two types of constraints can be distinguished; analytical constraints, describing the socio-economic condition and numerical conditions, describing the target-related environmental condition, expressed in CO_2-equivalent concentration and where c($\mathbf{X}$) is calculated by the simulation model IMAGE. The socio-economic constraints are related to restrictions on economic and social changes, such as changes of the gross national product.
The problem is now formulated as a constrained nonlinear optimization problem, which is complex by the nonlinearities in restrictions and the objective function. Besides, simulation runs with IMAGE are necessary for calculating the numerical constraint.

4.2.2 Global Optimization (General Introduction)

A general optimization problem can be formulated as follows. Find the values of the decision variables x, which satisfy the given constraints, that is a given set of equations and inequations and optimize the objective function f(x). An optimization problem is linear if the objective function and all the constraint functions are linear in the variables. All other problems are nonlinear. A problem is quadratic if the objective function is quadratic and if all constraints are linear. Convex problems are those with convex objective functions and linear restrictions. For these functions there are useful optimization methods called respectively linear, quadratic and convex programming.
For other non-linear problems, often called global optimization problems, no general methods exist. The difficulty of global optimizing can be illustrated as follows. A feasible point x^*, satisfying the constraints, is called a local minimum if a real number $\varepsilon>0$ exist such that

$$f(x^*) \leq f(x) \quad \forall \text{ feasible points } x$$

with $\| x-x^* \|<\varepsilon$. Every norm $\| \ \|$ on $\mathbb{R}^n$ can be chosen. A feasible point x^* is called a global minimum point if

$$f(x^*) \leq f(x) \quad \forall \text{ feasible points } x$$

Clearly a global minimum is a local one, but the converse is generally not true, because there can be many local minima. However, global optima are always local optima. Therefore several optimization methods involve techniques for finding local optima.

There are several optimality conditions for local optima. The necessary conditions of Kuhn-Tucker are the best known. Consider the following problem

$$\begin{aligned} &\min_{x \in \mathbb{R}^n} f(x) \\ &\textit{subject to} \\ &g_i(x) \leq 0, \quad i = 1,\ldots,k, \\ &h_i(x) = 0, \quad i = k+1,\ldots,r. \end{aligned} \tag{4.2}$$

where the objective and restriction functions are differentiable
Assume that the gradients of the active constraints, i.e. the vectors ∇h_i and ∇g_i are linearly independent. Using this constraint qualification the following theorem can be given.

Theorem 4.1 (Necessary Kuhn-Tucker conditions (Fiacco & McCormick, 1968)).
Necessary conditions for x^* to be a local minimum of 4.2 are that there exist vectors $u^* \in \mathbb{R}^k$ and $v^* \in \mathbf{R}^{r-k}$ such that:

$$
\begin{aligned}
&\nabla f(x^*) + \sum_{i=1}^{k} u_i^* \nabla g_i(x^*) + \sum_{i=k+1}^{r} v_i^* \nabla h_i(x^*) = 0, && \\
&\sum_{i=1}^{k} u_i^* g_i(x^*) = 0, && \\
&u_i^* \geq 0, && \textit{for } i = 1,\ldots,k, \\
&g_i(x^*) \leq 0, && i = 1,\ldots,k, \\
&h_i(x^*) = 0, && i = k+1,\ldots,r.
\end{aligned}
\qquad (4.3)
$$

The above qualifications are rather difficult to verify in practice. They are either only of theoretical interest or only of importance in special cases.

There are several methods for global optimization problems. They can be divided in two classes, deterministic and stochastic methods (Rinnooy Kan and Timmer, 1989). Deterministic methods involve additional assumptions on f(x) to provide a rigid guarantee of success. Stochastic methods have the possibility of an absolute guarantee of success under very mild conditions on f(x). However, the probability of success can be shown to approach 1 only as the sample size increases to infinity.

4.2.3 The Optimization Method

4.2.3.1 Introduction

To solve a constrained nonlinear optimization problem with a restriction which depends on model simulations is complex. In the developed optimization method we first solve a the problem without the numerical, environmental constraint (thus no model simulations) and afterwards the entire problem with model simulations. In the first step (Level 1), the environmental restriction is approximated by an analytical condition on the carbon budget of the period between 1990 and 2100 ($\Sigma_i\Sigma_r\ x_{i,r} \leq B$) and solved with a stochastic method[1], because such a method does not require much restrictions on the objective function. The derived solution of the first level is used in the second level to solve the original problem using the simulation model IMAGE. The numerical environment constraint is solved using an analytical expression of the CO_2-equivalent concentration, which constants c(**X**), represent CO_2 fluxes between the ocean-atmosphere and between the terrestrial biota-atmosphere and besides also the radiative forcing of non-CO_2 gases, are coming from IMAGE. Local searches are started, with a starting solution $\mathbf{X}^+$ (last local optimum), until the functionsvalues f($\mathbf{X}^+$) are feasible and converged.
The derived solution $\mathbf{X}^*$ is a feasible local optimum of the original problem. To improve the solution we return to level 1 with a carbon budget which is the sum of the emissions of the local optimum $\mathbf{X}^*$. After several rounds the solution does not improve anymore and the optimization method is stopped. A complete description of the optimization method is given in this section.

Figure 4.1 (next page): Scheme of the optimization method. Started with an initial global carbon budget (B), a simplified version of the problem is solved in the first level. The derived solution is given as input for the second level, where first the constants c(**X**) of the environmental restriction are calculated with IMAGE. Then a local optimum $\mathbf{X}^+$ of the original problem is found by one local search. Because c(**X**) change when **X** is changed, the constants are again calculated with IMAGE. If the solution $\mathbf{X}^+$ is feasible and the functionvalues are converged, a feasible local optimum $\mathbf{X}^*$ of the problem is found. If the local optima of the original problem $\mathbf{X}^*$ are converged, the method is stopped, otherwise a new local optimum will be found in the next round of level 1 and 2. To improve the solution, the global carbon budget is adapted after each local optimum, into the sum of emissions of the last optimum.

[1] In this study we used multistart (Timmer, 1984), which starts in several random starting points local search procedures until some stopping rule is satisfied.

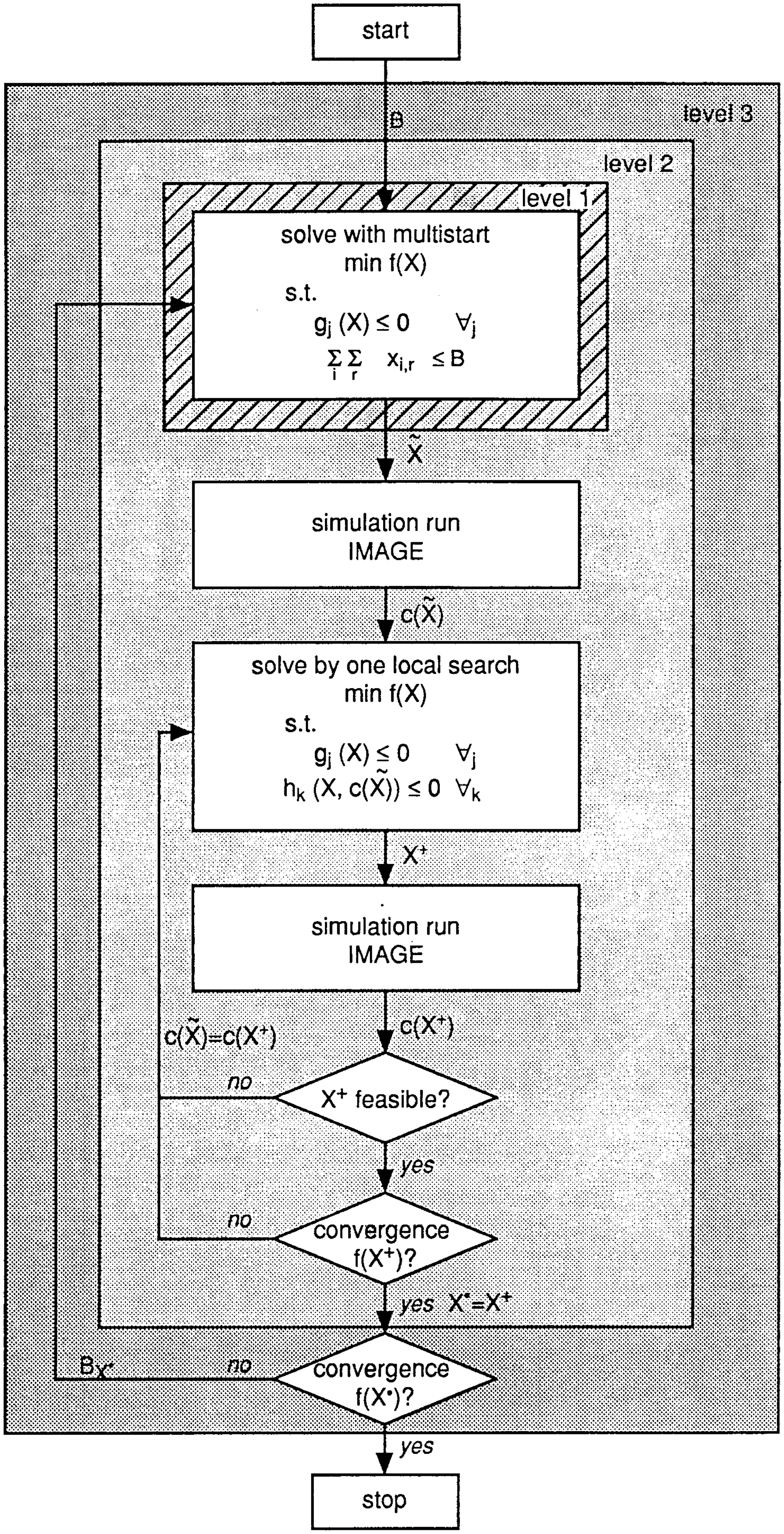

Figure 4.1
Scheme of the optimization method

4.2.3.2 Level 1

In this level the regional emissions are allocated optimal in time under a maximum global carbon budget. The starting budget can be chosen arbitrarily. The optimization problem is formulated in 4.1, although the environmental condition is replaced by a limited global carbon budget. A stochastic method, the so called multistart method, is used. This method does not use restrictive conditions on the objective functions. Several local searches are started until a stopping criterion is satisfied.

Multistart (General)

Step 1. Draw a point from a uniform distribution over S.
Step 2. Apply a local search to the new sample point.
Step 3. A termination criterion indicates whether to stop or to return to Step 1. The local minimum with the smallest function value is the candidate for the global minimum

Step 1
With $S \subset \mathbb{R}^n$ a set, which is convex, compact and contains the global minimum as an interior point. Here S is the set of random distributions of a given global carbon budget. An initial value for the budget can be chosen arbitrarity.

Step 2
Local search methods are strong instruments for investigating global optimization problems, since these methods can find local optima of a nonlinear function in a relative short time. Local search procedures in N-dimensional space use line minimization. Given a starting point $\mathbf{x}$, a direction $\mathbf{d}$ and a function $f(x)$, such a line minimization algorithm finds a scalar λ that minimizes $f(\mathbf{x} + \lambda\mathbf{d})$. Multidimensional methods only differ in the way in which, the next direction $\mathbf{d}$ is chosen. The local search procedure used is Powell's method (Press *et al.*, 1988). The Powell's method does not involve explicit computation of function's gradient to choose a successive direction. The algorithm tries all N possible directions with line minimization (N directions because the solution space can be described by N vectors). The direction which leads to the largest reduction of the objective function value is chosen as candidate direction. In Press *et al.* (1988) criteria are described of the direction, which had to be satisfied to examine again N directions with a direction set which is adapted for the chosen direction. A detailed description of this method is described in Press *et al.* (1988).
Because in this problem there is a time structure, one adaption of Powell's method is examined. Usually the starting directions of the local search are the basis vectors e_i. Because of the time dependence one can assume there is correlation between regional emissions at several timepoints. When emissions in region r on timepoint i increase, one may expect that emissions from that region on other timepoints near i may also increase. Note that the starting solution is a random one and the expectation is that a starting direction which assumed a time dependence will move faster into the direction of a local optimum. However, experiments indicate that no significant faster solutions can be derived without increasing the value of the average local optima. The difference of 25 years between the time points seems to fade away a strong correlation,

The above local search was based on finding a minimum for a function, without any constraint. However, in this study we deal with a problem with several constraints, such as a limitation on the global carbon budget. Therefore we implement penalty functions in the objective function. In this study the absolute value penalty function is used (Gill *et al.*, 1981).

$$\min_{X} \quad F(X) = f(X) + \rho \sum_{j \in J} |\hat{c}_j(X)| \tag{4.4}$$

with:

$$\hat{c}_j(X) = g_j(X), \qquad \textit{when } j \textit{ is an equality constraint,}$$

$$\hat{c}_j(X) = \max(0, g_j(X)), \quad \textit{when } j \textit{ is an inequality constraint.}$$

The vector $\hat{c}$ represent the constraints violated at **X**, which is defined by the set of J. If a constraint $\hat{c}$ is violated, f(**X**) get a penalty. There is a threshold value ρ_{max} such that a unconstrained minimum for F(**X**) exists for any $\rho_j > \rho_{max}$. This is in contrary to the quadratic penalty function ($\rho\hat{c}^T\hat{c}$) where ρ_j can be infinity to have an unconstrained minimum. Note that the resulting problem is nondifferentiable in contrary to quadratic functions. The resulting algorithm for a general constrained nondifferentiable problem is showed below (Gill *et al.*, 1981):

step 1. Solve the unconstrained subproblem F($\mathbf{X}_k$), with $\mathbf{X}_k$ as starting point and $\mathbf{X}_{k+1}$ the best point found by the Powell's method.

step 2. If k>0 goto *step 3.*
If $\rho > \rho_{max}$ the algorithm terminates with a failure.
If *step 1* fails to locate a 'satisfactory' minimum of F(**X**), or if $\mathbf{X}_{k+1}$ is not feasible, set $\rho = \gamma\rho$ with $\gamma>1$ and go back to *step 1*, otherwise go to *step 4.*

step 3. If $\mathbf{X}_{k+1}$ is not a 'significant better' solution than $\mathbf{X}_k$, the algorithm terminates with the 'better' of $\mathbf{X}_k$ and $\mathbf{X}_{k+1}$ as the solution.

step 4. $\rho = \rho/\gamma$
Goto *step 1*

If **X** is not feasible or if there not a 'satisfactory' minimum of F(**X**) found and the threshold value ρ_{max} is not exceeded, ρ will be increased γ times. We assume here that if a feasible optimum is found in step 1, this is a satisfactory minimum. The reduction of the penalty parameter in step 4 is included in order to try to improve the accuracy of the minimum in all directions.

Step 3

It can be shown that the solution of multistart converges to the global optimum. If $y^{(i)}$ is the smallest function value after i local searches, it is known that $y^{(i)}$ does converge to the global optimum y with probability 1 (Timmer, 1984). Stopping rules are used to stop multistart in finite time. Boender (1984) used a Bayesian approach to evaluate the effort and potential benefits of further runs. After every local search information is obtained of the distribution of the number of local minima and other parameters. This information is used to determine statistic expressions of keyparameters of the process. These distributions are dependent of an assumed form, which are called prior distributions. Using the information a posterior distribution can be estimated. Based on these expressions stopping rules are determined. The parameter used in this study is the expectation of the number of local optima that are not found. The expression is based on a Bayesian estimate of the number of local minima and the relative size of each region of attraction. When these variables are assumed to be random for which a prior distribution can be specified, the posterior expectation of this parameter can be estimated. The posterior expectation of the number of local minima (L_N) is (Boender, 1984)

$$E[L_N|W_N=w] = \frac{w(N-1)}{N-w-2} \qquad if\ N \geq w+3 \tag{4.5}$$

if w different local minima (W_N) have been found in N local searches, and assuming that each integer of $[1, \infty)$ is equally probable for the a priori number of local minima and that the relative sizes of attraction follow a uniform distribution.

Piccioni and Ramponi (1989) adapt the stopping rule when local minima have <u>different</u> function values and are only interested in location of the local minima with the smallest values. They derived the following (4.6) posterior expectation of the number of local minimum points (H_N) whose function value is smaller than those found in the sample.

$$E[H_N|W_N=w] = \frac{w}{(N-w-2)} \qquad if\ N \geq w+3 \tag{4.6}$$

A stopping rule can be

$$E[H_N|W_N=w] - w < \delta \tag{4.7}$$

which means that the expected number of (better) local optima not found is less than δ.
Numerical experiments showed that even if functions do not meet the basic conditions that different local minima points have different function values, the stopping rule can be used (Piccioni and Ramponi, 1989). Therefore the Piccioni and Ramponi stopping rule is used in this study.

When the method is just started, high accuracy is not necessary. The local optima found in the beginning of the method are of minor importance for the final solution. They are only used to derive a good direction. Therefore the accuracy is increased during the running of the method. Let N be the number of times the second level is runned and let δ be the maximum number of not found better local optima, then the condition can be rewritten as

$$E[H_N|W_N=w]\ -w < \delta(\varepsilon + \frac{1-\varepsilon}{N}) \qquad with\ 0 < \varepsilon < 1 \tag{4.8}$$

The stopping criterion is now δ in the first round (N=1) and become $\delta\varepsilon$ when the algorithm never ends. When the stopping rule is satisfied, the solution is used as starting vector of level 2.

4.2.3.3 Level 2

Solutions of the first level are optima of a simplification of the problem. In the second level a local optimum is calculated for the original problem. A global CO_2 emission scenario, based on the solution of the first level, is used as an input for the model IMAGE. IMAGE calculates the resulting CO_2-equivalent concentration, and thus whether the environmental condition holds for this solution. Besides IMAGE calculates the CO_2 fluxes between the ocean-atmosphere and between the terrestrial biota-atmosphere, and also calculates the radiative forcing.
At level 2 the optimization problem is defined with the environmental condition which is dependent of IMAGE, although it is analytical formulated in terms of the CO_2-fluxes between the ocean-atmosphere and between the terrestrial biota-atmosphere and radiative forcing of the non-CO_2 gases, as described below. Now this reformulated problem can be solved using Powell's local search procedure (see Level 1). This procedure initialized with the starting solution (optimum of the first level) finds a local optimum $\mathbf{X}^+$. In the next level 2-run IMAGE determines again whether this local optimum is feasible and the new fluxes and radiative forcing are calculated for this local optimum, then the local search procedure calculates a new local optimum with a start solution equal to the local optimum of the first level 2-run. Finally level 2 is ended after convergence of the feasible local optima to a local feasible optimum $\mathbf{X}^*$.
The accuracy of convergence is sharpen in this level during the method analogous to the method used at the first level. Let N be the number of times the second level is runned and $f(\mathbf{X}^+)_i$ is the local optimum of the i^{th} local search in the second level. The second level is stopped if the convergence criterium is satisfied: $|f(\mathbf{X}^+)_i - f(\mathbf{X}^+)_{i-1}| < \gamma\ (\varepsilon+(1-\varepsilon)/N)$ with $0<\varepsilon<1$. If not, a new local search is done starting from the last local optimum $\mathbf{X}^+$. The second level can be compared with the algorithm for a constrained global optimizing problem (Gill *et al.*, 1981). The main difference is that not penalty parameters, but the constants of the concentration restriction are changed after each local search.

Analytical environmental condition:

The CO_2 equivalent concentration can be expressed as equation 4.9 (Rotmans, 1990).

$$pCO_{2eq} = pCO_2in \cdot e^{[\frac{Ln(2)}{\Delta Q_{2xCO_2}} \cdot \Delta Q]} \tag{4.9}$$

with:

pCO_2in	= pre-industrial CO_2 concentration, in 1900 (ppmv)
pCO_{2eq}	= atmospheric CO_2 equivalent concentration (ppmv)
ΔQ	= total radiative forcing, caused by changes in concentrations of all trace gases (W/m^2)
ΔQ_{2xCO_2}	= radiative forcing for a doubled CO_2 concentration (equal to 4.3 W/m^2 according to the IPCC (1990)).

Changes in the concentration of radiative active trace gases result in corresponding changes in radiative forcing of the climate system. According to Ramanathan *et al.* (1979) the following approximate relation holds for the change in the radiative forcing by CO_2 emissions.

$$\Delta Q_{CO_2} = (\frac{\Delta Q_{2xCO_2}}{Ln(2)}) \cdot Ln(\frac{pCO_2}{pCO_2in}) \tag{4.10}$$

with:

ΔQ_{CO_2}	= change in radiative forcing by CO_2 (W/m^2)
pCO_2	= atmospheric CO_2 concentration (ppmv)

Using above equation and the fact that ΔQ is the total change in radiative forcing, defined as the sum of changes in radiative forcing by all trace gases ($=\Delta Q_{CO_2}+\Delta Q_{nonCO_2}$), the CO_2-equivalent concentration can be rewritten as follows:

$$pCO_{2eq} = pCO_2in \cdot e^{[\frac{Ln(2)}{\Delta Q_{2xCO_2}} \cdot (\Delta Q_{nonCO_2} + \frac{\Delta Q_{2xCO_2}}{Ln(2)} \cdot Ln(\frac{pCO_2}{pCO_2in}))]} \tag{4.11}$$

The atmospheric CO_2 concentration (4.12) is determined by the fossil fuel combustion, uptake of CO_2 by the oceans, flux of CO_2 from the terrestrial biota and the net ecosystem production flux, and can be modelled according to the following equation (Rotmans, 1990).

$$(4.12)\quad pCO_2(t)=pCO_2(t-1)+\int_{t-1}^{t} atmcf\cdot(FSEM(\tau)+OCEA(\tau)-TNEP(\tau)+THDIST(\tau))d\tau$$

with:

$pCO_2(t)$	= atmospheric CO_2 concentration at time t (ppmv)
atmcf	= factor that converts emissions of CO_2 into concentrations (ppmv/GtC)
FSEM(t)	= fossil fuel combustion flux at time t (GtC/yr)
OCEA(t)	= flux from oceanic mixed layers to the atmosphere at time t(GtC/yr)
TNEP(t)	= carbon flux by total net ecosystem production at time t(GtC/yr)
THDIST(t)	= total carbon flux of CO_2 due to human disturbance at time t (GtC/yr)

Using equation 4.11 and 4.12, the optimization problem can be formulated as in 4.13. The variables derived from calculations of IMAGE are: $\Delta Q(t)$, $\Delta Q_{CO_2}(t)$, OCEA(t), TNEP(t), THDIST(t). Model calculations show that the numerical and analytical CO_2 equivalent concentrations have a difference less then 0.5%, when the variables derived from IMAGE were not changed.

$$(4.13)\qquad \min_{X}\quad f(X)$$

$$(a)\quad pCO_2in\cdot e^{[\frac{Ln(2)}{\Delta Q_{2xco_2}}\cdot(\Delta Q(t)-\Delta Q_{co_2}(t)+\frac{\Delta Q_{2xco_2}}{Ln(2)}\cdot Ln(\frac{pCO_2(t)}{pCO_2in}))]}\leq CC(t)\qquad \forall\ t$$

$$(b)\quad pCO_2(t)=pCO_2(1990)+\sum_{\tau=1991}^{t} atmcf\cdot(FSEM(\tau)+OCEA(\tau)-TNEP(\tau)+THDIST(\tau))\quad \forall t$$

$$(c)\quad FSEM(t_i)=\sum_{r=1}^{\#r} x_{i,r}\qquad \forall\ i$$

$$(d)\quad FSEM(\tau)=FSEM(t_{i-1})+(FSEM(t_i)-FSEM(t_{i-1}))\cdot\frac{(\tau-t_{i-1})}{(t_i-t_{i-1})}\qquad \forall\tau\in[t_{i-1},..,t_i].\ \ \forall i$$

$$with\quad x_{i,r}\geq 0\qquad \forall\ i,r$$

with:

$x_{i,r}$	= fossil fuel combustion flux at timepoint i in region r (GtC/yr)
CC(t)	= target-related CO_2-equivalent concentration level (ppmv)

4.2.3.4 Level 3

The first two levels together find a local optimum of the original problem. The third level determines whether one may expect a significant improvement based on a convergence criterion: The difference between present solution $f(\mathbf{X}^*)$ and $f(\mathbf{X}^*)$ of the last round is larger then a small value. If the solution is expected to improve, the algorithm returns to level 1 with a new carbon budget (for the simplified environmental restriction), which is the sum of emissions of the local optimum as derived in level 2. Otherwise the algorithm is terminated. Because the first level enables us to find a good starting solution for the second level, the adaption of the maximum global carbon budget (B), derived from a feasible local optimum of level 2, will improve the next solution of level 2.

In Figure 4.2[2] we show the behaviour of local optima during the running of the optimization method in an example. Given an arbitrary carbon budget in the first level, multistart is used to find a local optimum of the simplified problem. When the stopping rule is satisfied, an optimum is found for the simplified problem. In level 2 feasible and non-feasible solutions are found, using an analytical expression of the CO_2-equivalent concentration and updating the constants by simulation runs of IMAGE. This level is stopped when a feasible solution is found, which is converged. This solution is a local optimum of the original problem. Returning to level 1 with an adaption of the global carbon budget results in a significant improvement of the local optima. After several rounds (runnings of level 1 and 2), no further significant improvement is derived and the optimization algorithm is stopped.

Figure 4.2 indicates that the method is an useful instrument to find a suboptimal solution for a constrained nonlinear problem with interactions with a simulation model. However, it is not known whether the method converges to the global solution, but for different starting budgets the solution converged to the same optimum (Figure 4.3). Also the budgets converged to the same amount (Figure 4.4). This figure also shows that better starting budgets lead to faster convergence.
The adaption of the global carbon budget improves the solution because the objective function determines the form of the emission paths (in level 1), and this will only be change if the concentration restriction makes it necessary or if the solution can be improved by increasing the global carbon budget (in level 2).

The algorithm can be compared with multistart. Several local searches (level 1+2) are done until some stopping rule is satisfied. A difference is that the starting solution for the next round (level 1), is random for an adapted solution space (S). Also in this optimization method the local optima converges in contrary to general multistart, where the best optimum is chosen from a set of different local optima.

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[2] The optimization method is implemented in FORTRAN and runs on a SUN SPARC Workstation. The FORTRAN version of IMAGE is somewhat different than IMAGE 1.0 (den Elzen *et al.*, 1991a,b). The most important difference is the incorporation of some feedback processes in the carbon cycle and the methane module (den Elzen *et al.* 1991c).

The running time of the method depends on several factors: the number of local minima, the starting global carbon budget, the convergence criterion, the stopping rule, the number of function-evaluations of a local search, the number of constraints and the computing time of one function evaluation. Therefore on the one hand the running time can vary for different problems, but on the other hand one can adapt some parameters, such as stopping rules and convergence criteria, to speed up the running time. However, adapting stopping rules and convergence criteria could lower the quality of the solution.
Note that only several times IMAGE is runned (Figure 4.2 and 4.3) and that the running time of the algorithm largely depends on the first level when different local optima exist. Because the objective function is poorly known, a robust optimization method has been developed. But when some function is formulated it can be recommendable to solve the first level with an other optimization method. For linear, quadratic and convex objective functions with linear restrictions there are useful methods called respectively linear, quadratic and convex programming. Using these methods, the running time can be decreased and the quality of the solution can be increased.

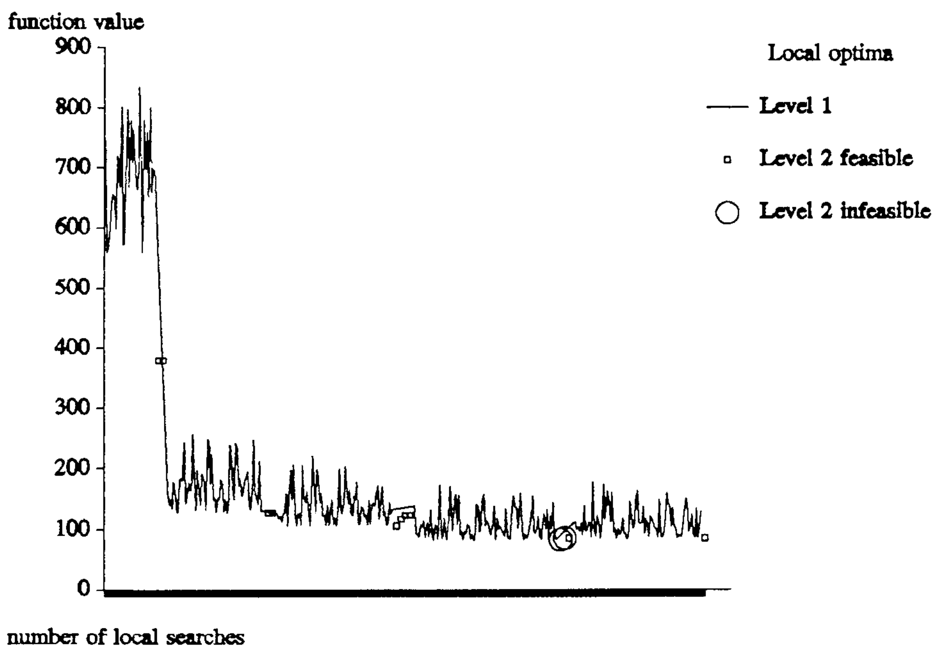

Figure 4.2: An example of the values of local optima during the optimization method.

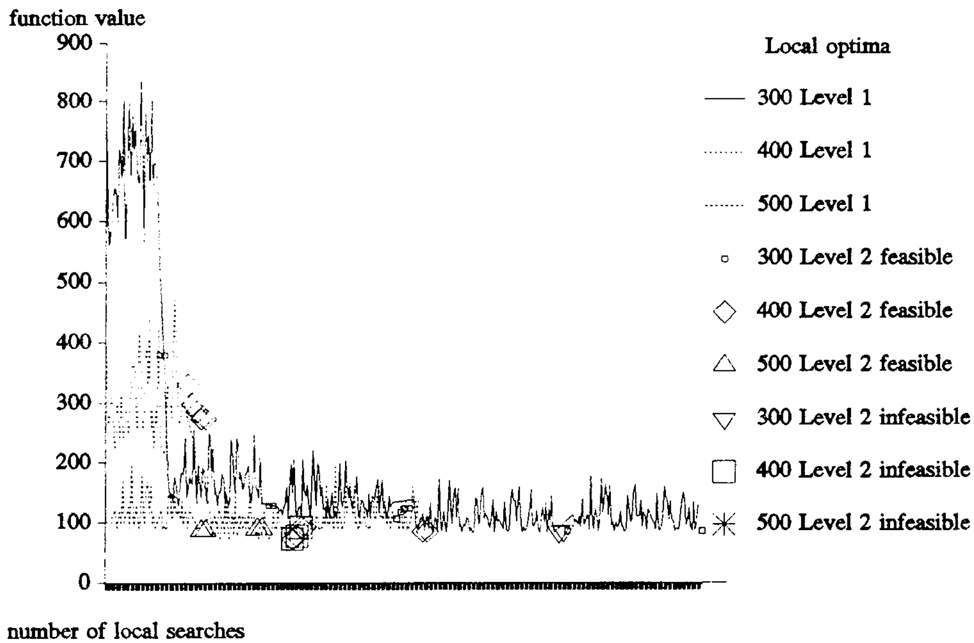

Figure 4.3: Values of local optima during the optimization method when different carbon budgets are used as starting value in level 1.

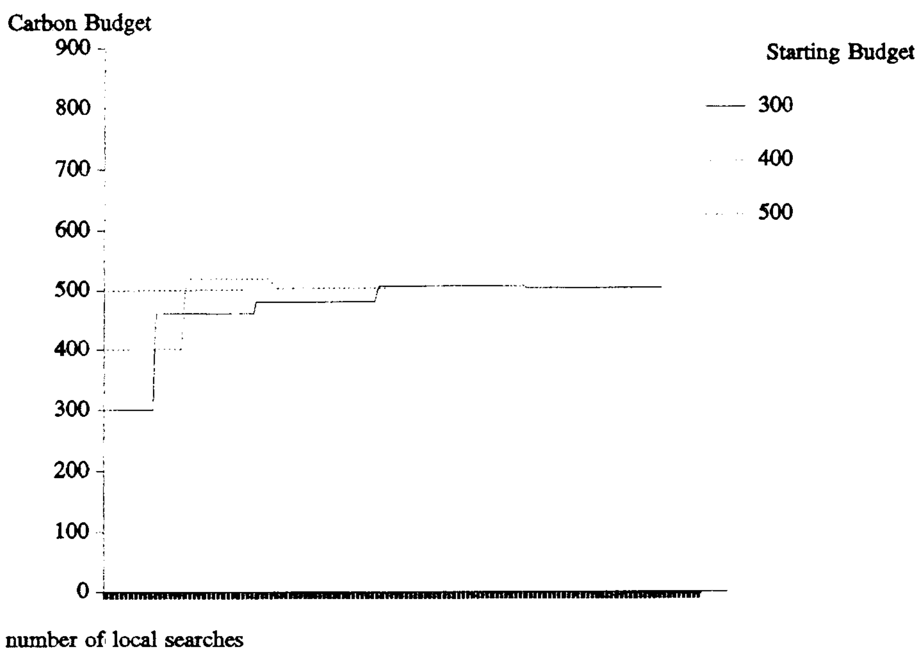

Figure 4.4: The carbon budget during the optimization method when different budgets are used as starting value.

4.3 Objective Functions

4.3.1 Introduction

In the previous section an optimization method for the optimization problem has been discussed. This method finds a suboptimal allocation of regional CO_2 emission paths with respect to an objective function. Such a function takes account of economic, social and ethical aspects of the allocation of emission permits. This section presents rough estimates for those functions, since reliable assessments of cost and benefits of policies, which are necessary to quantify the economic objective function, are still not available.
Here we distinguish three kinds of objective functions: the economic objective function, which minimizes economic consequences (cost) of CO_2 emission reductions, the utility objective function, which maximizes the social and ethical values, and finally the objective function, which is a mixture of both. These functions are defined here as respectively conservative, progressive and mixed forces. These objective functions are highly uncertain, because of all possible future developments in their components such as: economy, politics, technology, population growth, etc.

4.3.2 Conservative Forces

4.3.2.1 Cost Minimization

Policies which involve stabilizing or reducing emissions of carbon dioxide, requires significant changes in industrial technology and may have profound economic impacts on modern societies. Although there is growing evidence that the first steps towards this goal will not be very costly (RIVM, 1991) and in fact, maybe even profitable and often serving other desirable goals as well, emission reductions will involve cost. An efficient allocation of regional emission reductions can minimize the total cost. This would imply reduction measures in those regions where the cost is relative low.

Cost functions for carbon emission reductions are usually estimates using energy/economic models. When several reduction targets for the end-years are taken, price policy determines the discounted gross cost of such a target. This price policy is often modelled by carbon taxes. Increased carbon taxes are assumed to cause a shift to cleaner energy sources and to a more efficient use of energy and thus CO_2 emission reduction. The cost of a reduction target are the investments into other energy sources and a more efficient use of energy, minus the extra governmental income from higher carbon taxes. After several targets, the net cost, relative to the reference scenario (no reductions), are used to determine cost functions like those as depicted in Figure 4.5.
Cost functions of reduction of carbon emissions have different shapes in different studies (Figure 4.5). Edmonds and Barns (1990) and Ingham and Ulph (1991) derive monotone increasing functions. However, Ayres and Walter (1991) argue that also other shapes could exist, where reductions will pay in first instance. Such a curve assumes that there is an economic disequilibrium and are found by scenario study by Gusbin *et al.* (1990), for different European countries. In Gusbin *et al.* these kind of cost functions are derived by using databases of energy efficiency and conservation.

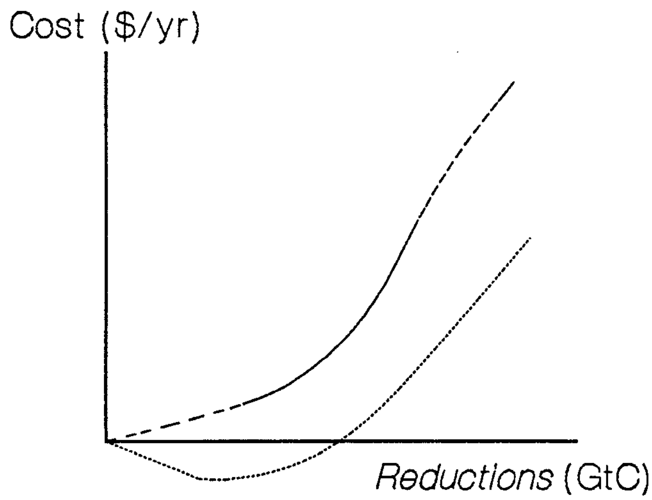

Figure 4.5: Different indicative curves of total cost of reducing carbon emissions. The lowest curve indicates an economic disequilibrium.

The above studies, however, cannot be used in our study, since here the objective function should take into account a time- and regional component. Therefore we developed an analytical cost function (thus not dependent of a simulation model).
General cost functions are concave in prices (which means that they increase with ever faster rates), are continue and lead to higher cost if prices increase. Finally, multiplying prices by a positive scalar does not change the composition of a cost minimizing bundle (Varian, 1984)
Cost can generally be separated into fixed and variable cost. Short run initial cost may involve investment cost of equipment and buildings and variable cost, for instance labour cost. Because of the long time horizon in this problem, we consider all costs as variable costs.

We assume that increasing emission reductions lead to monotone increasing cost (thus assuming an economic equilibrium). The reduction cost is also dependent of technical improvements and regional aspects. This is modelled by a factor CF(t,r) which is an indicative measure for converting carbon reductions (relative to $x_{t_0,r}$, which are the present emissions) to cost. An indicative cost function can be formulated as equation 4.14.

$$C_{t,r}(RED(t,r)) = \frac{CF(t,r) \cdot x_{t_0,r} \cdot RED(t,r)}{1 - RED(t,r)} \tag{4.14}$$

with:

$C_{t,r}(RED(t,r))$ = *total costs of region r after* $t - t_0$ *years* (*in* $)

$RED(t_i,r)$ = $\max(0, \frac{x_{t_0,r} - x_{t,r}}{x_{t_0,r}})$

$CF(t,r)$ = *cost factor, the price of reducing C in region runtil year t* (*in* $/GtC)

Equation 4.14 can be written as:

$$C_{t,r}(x_{t,r}) = \frac{CF(t,r)\cdot x_{t_0,r}\cdot(x_{t_0,r}-x_{t,r})}{x_{t,r}} \quad if\ x_{t,r}<x_{t-1,r} \tag{4.15}$$

$$= 0 \qquad otherwise$$

Cost of reduction is assumed to decline in time by technical innovation. We assume that the relative cost is reduced in time by the energy intensity[3] improvements, the most important method of reducing carbon dioxide emissions in scenario models. This is modelled by the factor δ_t (in the exponent in equation 4.16), which is the average percentual improvement of the energy intensity over the period 1990 till year t. This improvement of energy intensity is assumed to increase in time with 1.0 and 2.5 percent in the beginning of the period of interest and decrease between 0.7 to 1.8 percent at the end of the next century (IPCC, 1991). In chapter 5 we assume for the reference case that the energy intension improvement declines from an annual rate of 1.6 percent in 1990 to 1.2 percent in 2100, which is the average of the midvalues of the moderate and the high efficiency case.

The relative cost of reducing emissions is assumed to vary among the regions and are assumed to be dependent of the emissions per capita. Reduction cost is expected to decline in a diminishing rate when emissions per capita are increased. Although the cost of reduction depends on the stage of economic development, we think this assumption can be used as an indication of regional cost aspects. The regional dependent cost factor is modelled as a logarithm of emission per capita (in tC), where a constant value 1 is added to avoid negative values (4.16). The indicative cost conversion factor is for simplicity assumed to be equal to 1.

The regional and time dependent cost factor is now modelled as

$$cf_{t,r}(x_{t,r}) = CCF\cdot\frac{e^{-\delta_t\cdot(t-t_0)}}{\ln\left(\dfrac{x_{t,r}}{pop(t,r)}+1\right)} \tag{4.16}$$

with

δ_t = parameter which indicate the technical innovation rate

CCF = factor which converts the expression into dollars ($\$(tC\ per\ capita)^{-1}$)

The reduction cost in year t is the difference between cost of reduction until t ($C_{t,r}(x_{t,r})$) minus the reduction cost until year t-1 ($C_{t-1,r}(x_{t-1,r})$). When CF(t,r) and CF(t-1,r) are replaced by $cf_{t,r}(x_{t,r})$ it gives the final expression for the yearly cost in region r at time t of the strategy $\mathbf{x}_r$.

[3] Energy intensity is relative amount of energy per unit of GNP.

$$YC_{t,r}(x_r) = \left(\frac{x_{t_0,r} - x_{t,r}}{x_{t,r}} - \frac{x_{t_0,r} - x_{t-1,r}}{x_{t-1,r}}\right) \cdot \frac{CCF \cdot x_{t_0,r} \cdot e^{-\delta_t \cdot (t - t_0)}}{\ln(\frac{x_{t,r}}{pop(t,r)} + 1)} \qquad if\ x_t < x_{t-1} \tag{4.17}$$

$$= 0 \qquad otherwise$$

The total cost till year t can now be expressed as the sum of the annual cost:

$$C(X)_t = \sum_r \sum_{y=t_0}^{t} YC_{t,r}(t, x_r) \tag{4.18}$$

This derived cost function has many limitations, and perhaps cost functions derived from calculations with an energy/economy model can give more reliable estimates. In this study we use this cost function only as an indicative function to get more insight in the cost optimal regional allocation of the emission reductions.

Although cost of CO_2-emission reduction vary with the methods used, the uncertainties in damage cost of climate change are even larger. Regional projections of future climate changes are presently highly uncertain, and the involved cost for the society and ecosystems at regional level are difficult to quantify. Ayres and Walter (1991) give preliminary estimates of this cost, which vary largely in magnitude. Peck and Teisberg (1991) show that even the form of damage cost functions have large influence on response strategies. When the estimates of this damage cost are more reliable, an optimization could be based on a cost-benefit objective function.

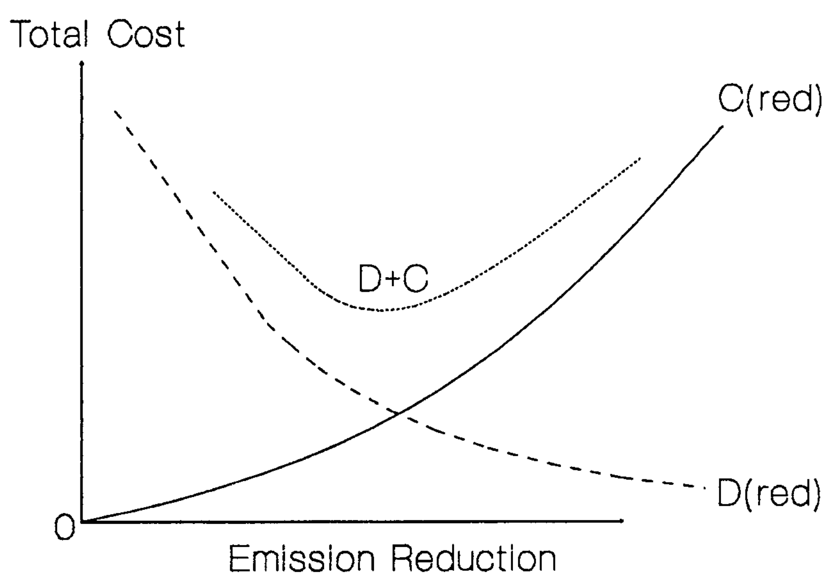

Figure 4.6: Total cost of reduction of carbon emissions C(red) and total damage cost D(red).

4.3.3 Progressive Forces

4.3.3.1 Utility Maximization

In general, utility theory deals with the desirability of outcomes of economic processes. Welfare of a consumer is examined with efficiency and equity aspects. People are assumed to maximize their utility. They are assumed to be rational decision makers and value extra products along a diminishing marginal rate (Varian, 1984). The law of diminishing marginal utility is shown in Figure 4.7. The utility function of welfare is a monotone increasing function ($du/dc>0$) but the more welfare one has, the less extra utility one values an welfare unit ($d^2u/dc^2<0$).

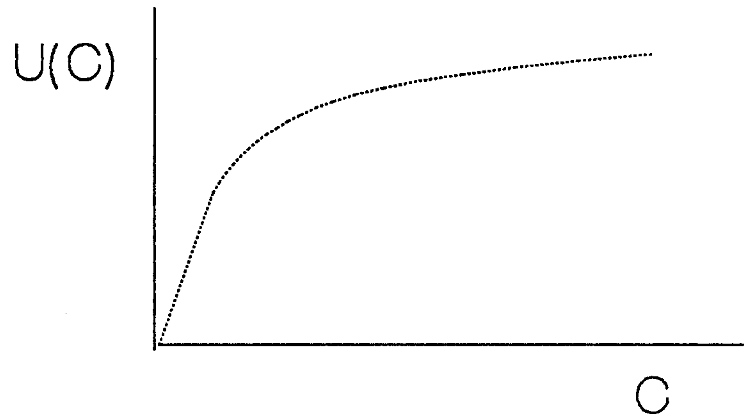

Figure 4.7: Utility values (U(C)) dependent of consumption (C)

In Figure 4.8 some indifference curves are given for two goods (X and Y). If the distribution of goods is changed and the new distribution is lying on the same indifference curve, the utility for the consumer remains the same. In Figure 4.8 also a budgetline is given. On this line we have to find the distribution U^* which maximizes the utility. Other distributions will be on a lower indifference curve and therefore have a lower utility.

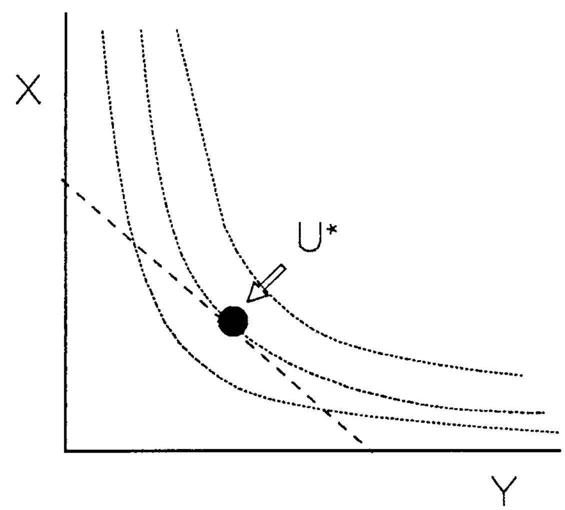

Figure 4.8: Utility Maximization. The total budget of a consumer must be distributed between goods X and Y. The given budgetline (- -) maximizes utility of the consumer given the indifference curves (...).

The utility theory of a consumer as described above can be translated to a set of consumers distributing the resources to persons contrary to goods. De Vries (1988) used the concept of utility as a value measure to be attached to the demand for an exhaustible resource. Therefore he discussed the following form of an (iso-elastic) utility function (4.19).

$$U(C) = \frac{C^{1-e}}{1-e}, \qquad \textit{for } e \neq 1,$$

$$U(C) = \ln C, \qquad \textit{if } e = 1.$$

with: (4.19)

C = *Consumption*

$$e = \textit{elasticity of marginal utility} \; \left(= -\frac{d\ln(\frac{dU}{dC})}{d\ln C}\right)$$

Utility is sensitive for the value of elasticity. For an e-value smaller than 1, utility has no upperbound, if the e-value is larger than 1 utility becomes negative and has a upperbound. Figure 4.9 shows the utility function for some e-values of e (> 1). Higher e-values cause that very low consumption is valued much lesser than higher consumption. With lower e values, this difference is less extreme. Higher e-values will cause therefore a more equal distribution of resources over consumers when the total utility is maximized.

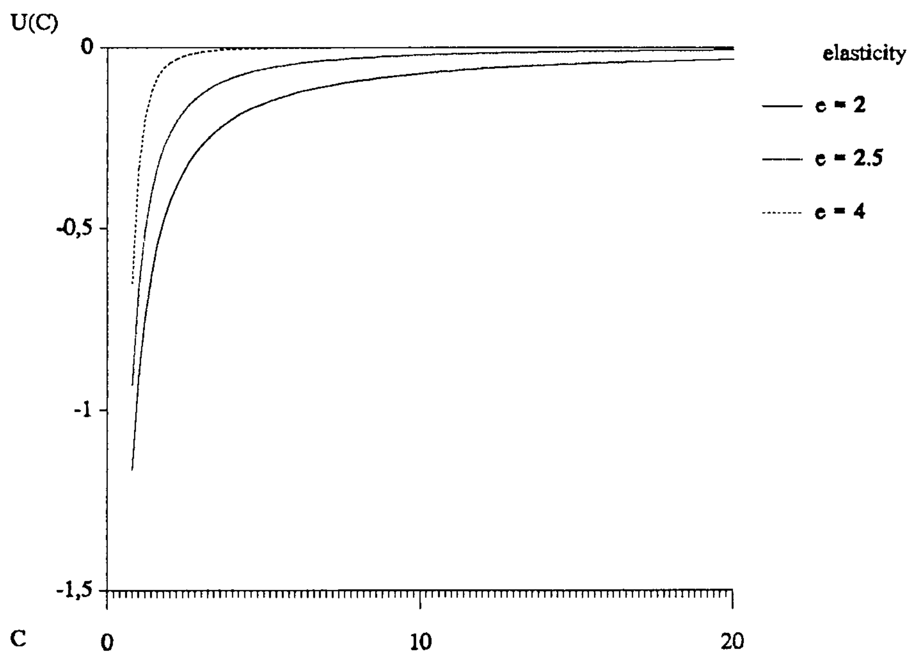

Figure 4.9: Utility values as a function for different values of the elasticity of marginal utility

As a first step for developing an utility function for this study we use GNP per capita as an indicator of consumption, where a linear relation between GNP and carbon emissions is used[4]. Such a relation is given in equation 4.20. We modelled here also the yearly energy intensity improvements of an economy by a factor ei_y. GNP is now a linear function of α_r (in \$/GtC), the region dependent factor of carbon intensity of the economy (values given in Appendix 6) and the time dependent factor ei_t of yearly relative energy intensity improvements. The moderate and high efficiency case of IPCC (1991) are used to determine a range of ei_t. In the reference case, as used in chapter 5, we use the average rate of the moderate and the high efficiency cases.

$$GNP_{t,r}(x_{t,r}) = \prod_{y}^{t} ei_y \cdot \alpha_r \cdot x_{t,r} \tag{4.20}$$

Note that we assume that the carbon intensity[5] of the energy supply remains the same, which means that we assume that no changes in the fuel mix occur, because converting energy from one form to another depends on several economic circumstances, such as energy prices, which are not modelled here.

The utility of a person in region r in year t can now be modelled as 4.21.

$$U_{t,r}(x_{t,r}) = \frac{\left(\dfrac{GNP_{t,r}(x_{t,r})}{pop(t,r)}\right)^{1-e}}{1-e} \tag{4.21}$$

The total world utility for the entire period is the sum of utilities, over persons and time.

$$U(X) = \sum_{r} \sum_{t} pop(t,r) \cdot U_{t,r}(x_{t,r}) \tag{4.22}$$

To avoid large economic changes and unreasonable changes in emission paths, the yearly change of GNP is restricted, when we maximize utility. In the reference case we will restrict the yearly GNP growth between 0% and 6%. The upperbound restriction is higher than the yearly regional GNP prospects of the high economic growth case as used by the IPCC (1991).

[4] Results of linear regressions are summerized in Appendix 6.

[5] Carbon intensity of energy supply is the relative amount of carbon emissions per unit of energy production.

4.3.3.2 Emission Debt Factor

In the objective functions so far, the historical regional carbon emissions are neglected. However, in chapter 3 is shown that most regions have built an emission debt. Results of the budget approach show that remaining budgets of developed regions are much lower than present emissions per capita, while some developing regions are allowed to increase their emissions per capita with a small amount. With the optimization method the emission permits can be estimated in a dynamical way in time. Using the budget approach emission debt can be modelled as equation 4.23. When some scenario is chosen for non-CO_2 gases, given an emission scenario, the emission debt can be estimated. Because during the optimization algorithm, emission scenarios change, and so Q_{cap} changes and therefore the emission debt

$$(4.23)\quad ED_{t,r}(X) = \sum_{y=1800}^{1990} EM(y,r) + \sum_{y=1991}^{t} (x_{y,r} + EM_{luc}(y,r)) - Q_{cap}(X) \cdot \sum_{y=1800}^{t} pop(y,r)$$

with :

$$Q_{cap}(X) = \frac{\sum_{r=1}^{11} (\sum_{y=1800}^{1990} EM(y,r) + \sum_{y=1991}^{2100} x_{y,r} + EM_{luc}(y,r))}{\sum_{r=1}^{11} \sum_{y=1800}^{2100} pop(y,r)}$$

with:

$ED_{t,r}(X)$	= emission debt in year t of region r (GtC/yr)
$EM(t,r)$	= historical emission flux of carbon (GtC/yr)
$EM_{luc}(t,r)$	= future carbon flux by land use changes (GtC/yr)
$x_{t,r}$	= future fossil fuel combustion flux (GtC/yr)
$pop(t,r)$	= population size (billion persons)
$Q_{cap}(X)$	= average amount of carbon which may be emitted by every capita each year (tC/capita*yr)

One way to use ED for allocation of emission permits is to take account of ED in the utility approach. This cause lower emission permits for regions with debts, and higher permits for regions with emission credits. We now can model utility as 4.24.

$$U(X) = \sum_{r} \sum_{t} \frac{\left(\frac{GNP(x_{t,r}) + \xi \cdot ED_{t,r}(X)}{pop(t,r)}\right)^{1-e}}{1-e} \cdot pop(t,r) \qquad (4.24)$$

with:

ξ	= weight parameter (in \$/GtC)

4.3.4 Mixed Forces

The different objective functions as described above deal only with either economic or social consequences. Because decision making is a process of comparing the pro's and the cons of both economic and social aspects we investigate an objective function which is a mix of both forces (4.25).

$$f(X) = \alpha \cdot c(X) + \beta \cdot p(X) \tag{4.25}$$

with

f(**X**)	= mixed forces objective function
c(**X**)	= conservative objective function
p(**X**)	= progressive objective function
X	= regional carbon emission paths
α,ß	= weighting factors

Because both forces could have different units and orders of magnitude, it is difficult to estimate α and ß in such a way that we know which force will dominate. We estimate α and ß in the following way. First a local optimum is determined for both forces apart to estimate the order of magnitude. The objective function values are $c(\mathbf{X}^c)$ and $p(\mathbf{X}^p)$, with $\mathbf{X}^c$ and $\mathbf{X}^p$ the optimal solutions of the different problems.
After this α_0 and β_0, weighting factors of the forces, are divided by the objective function values of the two different local searches to derive α and ß; $\alpha = \alpha_0/c(\mathbf{X}^c)$, $\beta = \beta_0/p(\mathbf{X}^p)$. The resulting weighting values α and ß are now used to derive the mixed forces objective function.
When we find a global optimum $f(\mathbf{X}^*)$, we check the order of magnitude of the weighting factors by multistart for each force. When they differ not significant the algorithm terminates, otherwise we continue the optimization algorithm again with the new weighting factors until again $f(\mathbf{X}^*)$ converge.

4.4 Global Allocation

4.4.1 Introduction

The optimization method is developed for allocation of regional carbon emissions but it can also be used for allocation of global emissions. In this section we show two possible exercises where the method can be used for. The first one is a maximization of the global carbon budget and the second one a minimization of the difference between a reference scenario and a scenario which reaches some predetermined concentration value. These exercises are rather academical but give some ideas about the use of optimization techniques for scenario analysis.

4.4.2 Maximizing the Global Carbon Budget

Maximum global carbon budgets give information about the upperbound of the amount of carbon which may be emitted in the next 110 years. We are not only interested in the amount, also in the form of the emission path. We have restricted the form of the emission path to reach reasonable solutions. It is assumed that after reductions are taken, no increase of emissions are allowed (restriction (e) in 4.26). This restriction seems to be reasonable and enables the optimization algorithm to find a good solution in reasonable time. The problem is now formulated as 4.26 with y_i the global carbon emission of timepoint i (t_i).

$$(4.26) \quad \min_{Y} \quad -\sum_{i=1}^{\#i} (y_i - y_{i-1}) \frac{(t_i - t_{i-1})}{2}$$

$(a)..(d)$ *as* (4.13)

$(e) \quad y_i \le y_j \qquad \forall\ i>j \text{ and } j \ge z^* \text{ with } z^* = \min\{z \mid y_z \le y_{z-1},\ z \in \mathbb{N}\}$

with :

$$y_i = \sum_r x_{i,r}$$

Note that for maximizing the carbon budget, we cannot use the simplification of the problem (budget restriction) in level 1, because the carbon budget has to be a variable in this maximization problem. Therefore we adapt level 1, in which we first run IMAGE and solve than with multistart the original problem, thus with use of the analytical expression of CO_2-equivalent concentration. The remaining part (level 2&3) of the optimization method remains the same.

Solving the problem with the optimization method with different starting points, it appeared that not all local optima converged to the same solution (Figure 4.10). When a starting scenario was given with a small budget, this resulted in bad local optima. This may be caused by the fact that in level 1 already the difficult problem has to be solved. This problem can be solved by linear programming when the concentration restriction will be expressed into a linear function.

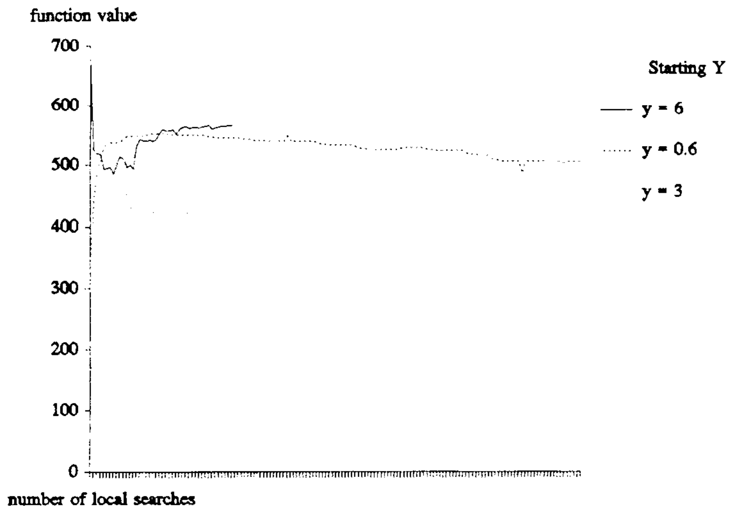

Figure 4.10: Local optima of maximizing the carbonbudget using different starting solutions.

4.4.3 Minimizing the Difference with a Reference Scenario

Suppose one wants to follow a scenario as good as possible, but wants to reach a lower CO_2 equivalent concentration level. This problem can be formulated as minimizing the change of the reference scenario (scen(t)) in (4.27).

$$\min_{X} \sum_{t=1991}^{2000} (scen(t) - FSEM(t))^2 \tag{4.27}$$

$$s.t. \quad (a)..(d) \; as \; (4.13)$$

4.5 Discussion

Allocation of future regional carbon emissions by fossil fuel combustion can be formulated as an optimization problem. Given a climate target dependent CO_2-equivalent concentration restriction the social and economic consequences of a regional allocation in time have to be optimized. This problem is formulated as a constrained nonlinear optimization problem. The developed method is successful in finding a suboptimal solution of a constrained optimization problem with a numerical restriction, which is dependent of a simulation model. The derived method is an adapted version of the multistart method, where different local searches are started until it is expected that no improvement can to be derived. The local search consists of two levels in which first a simplification of the problem is solved, and afterwards that the original problem.

The method can be used for different non-linear objective functions and can probably also be used for optimization problems of other environmental problems (when the decision variables are continuous).

To derive test problems, we developed several rough estimates of analytical objective functions (instead of simulation models), such as cost and utility functions. These functions can be used for the optimization method to give an indication of the consequences of specific optimization problems.

The optimization problem and method can be enlarged by taking account of other tracegases and environmental restrictions. Also the objective function can be improved by using, for example, a meta energy model, which can give us a better description of the structure of energy and economic systems.

5 Results of Allocating Carbon Emissions

5.1 Introduction

To show that optimization can be of great theoretical and practical importance in developing future climate strategies, we will discuss in this chapter several exercises with the optimization method as described in chapter 4. The optimization method allocates regional CO_2 emissions by fossil fuel combustion optimally with respect to an objective function, which quantifies the socio-economic consequences of emission-strategies, and which meets the climate targets. Since reliable objective functions are still not available, the method is only used for rough versions of these functions, which have been described in section 4.3. The climate target restrictions are modelled by an upperbound on the CO_2 equivalent concentration, as discussed in section 2. The emissions of non-CO_2 gases and the development of deforestation are assumed to follow the target dependent scenario.
The structure of this chapter is as follows: in section 5.2 we first discuss the optimization method for global allocation to maximize the carbon budget under climate targets and to minimize the difference with a predetermined scenario. Section 5.3 discusses the exercises with the optimization method for regional allocation to minimize cost and/or maximize utility. For each function we first present the reference case in which we use the concentration stabilization target as climate target. Secondly we present for each objective function several case studies where we consider the upper and lower boundary of the different parameters in the function. Besides we present for the central estimates of the function-parameters the calculations of the optimization method for two other cases 1) the two other climate targets: absolute and relative temperature target and 2) other non-CO_2 greenhouse gases and the development of deforestation following the Business-as-Usual scenario.

5.2 Global Allocation

5.2.1 Maximizing the Global Carbon Budget

5.2.1.1 Reference Case

A maximum of the remaining carbon budget can give an estimate of an upperbound of the amount of carbon which can be emitted in the next 110 years to meet a climate target. For the reference target (concentration stabilization target) the results of the maximization of the remaining carbon budget are presented in Figure 5.1. This figure shows the CO_2 emission paths due to fossil fuel combustion. The maximum global carbon budget of carbon emissions due to fossil fuel combustion, as calculated with the optimization method, for the concentration stabilization target is 620 GtC, 8 percent larger then the remaining carbon budget belonging to the adapted Control Policies scenario. The CO_2-emission paths, which lead to the maximum budget (Figure 5.1), show clearly that the largest part of the CO_2-flux is in the beginning of the period. This result was expected because in that situation a large amount of this flux can be removed from the atmosphere by natural processes over the next decades. The derived emission paths are not realistic, but give a theoretical upperbound on the carbon budget. The resulting CO_2 equivalent concentrations, depicted in Figure 5.2, show a sharp increase in the beginning of the period followed by a stabilization. Below we discuss carbon budgets for other targets and other scenarios for non-CO_2 gases.

5.2.1.2. Case studies

1. Climate targets

For the two other temperature targets, absolute temperature target and relative temperature target the resulting maximized remaining carbon budget is resp. 540 GtC and 410 GtC (Figure 5.1), resp. 15 and 17 percent larger than the corresponding budgets for fossil fuel combustion.

2. Non CO_2 greenhouse gases

If the non CO_2-gases follow the Business-as-Usual scenario instead of the reference case, the maximum budget is calculated to be 160 GtC, which is 460 GtC lower. If the non-CO_2 gases follow the Business-as-Usual scenario the other two climate targets will not be reached (Figure 5.2). This emphasizes that the role of non-CO_2-gases is not to be neglected in any negotiation about emission reductions.

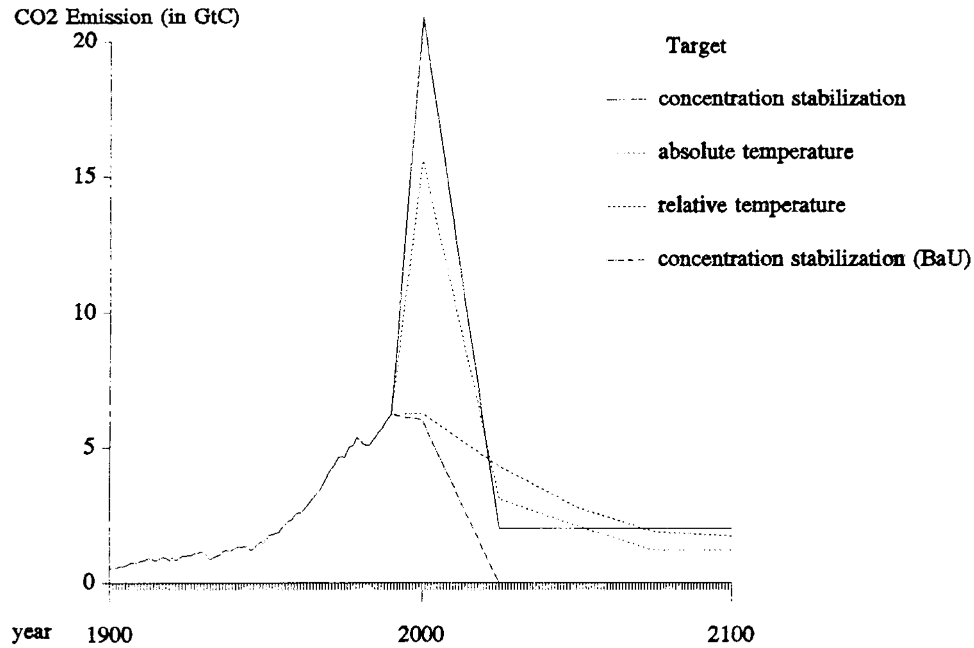

Figure 5.1: Carbon emission scenarios which lead to a maximum scenario for different targets.

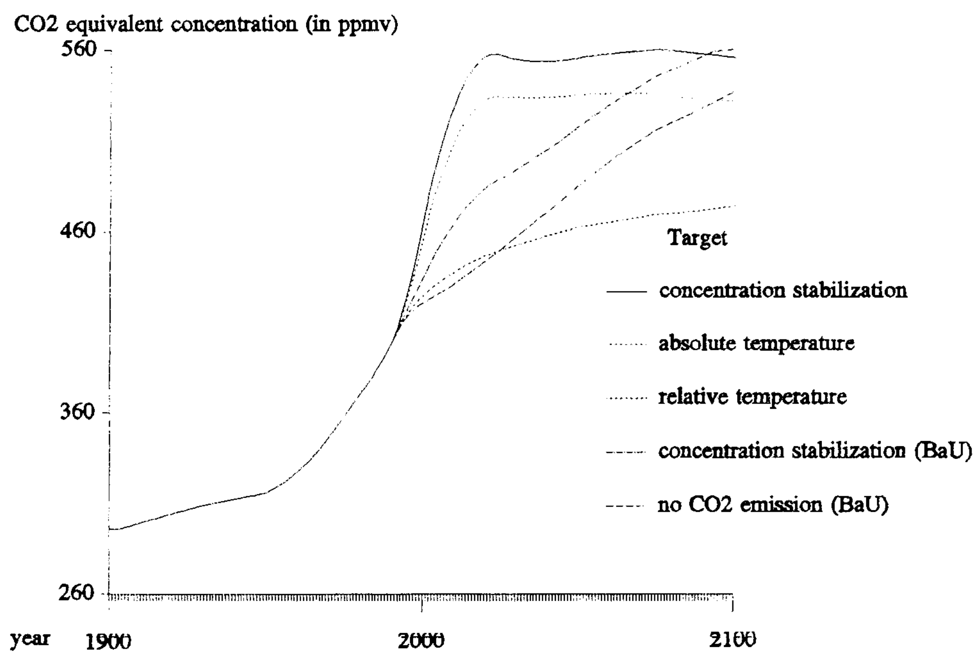

Figure 5.2: CO_2 equivalent concentration paths when a maximum of carbon is emitted but which does not exceed the concentration restriction.

5.2.2 Minimizing the Differences with a Reference Scenario

With the optimization method we can develop a scenario, which follows as close as possible the IPCC Control Policies scenario, on the restriction that the outcome achieves the concentration target of 560 ppmv in 2100. Because the quadratic value term of the objective function of the differences, the difference between the calculated and the original scenario is about the same (20% lower) over the whole period (Figure 5.3). This results in a concentration path with the same form as the original one, but with a lower stabilization level (Figure 5.4).
This example is just one of the many possible exercises using optimization techniques in scenario analysis.

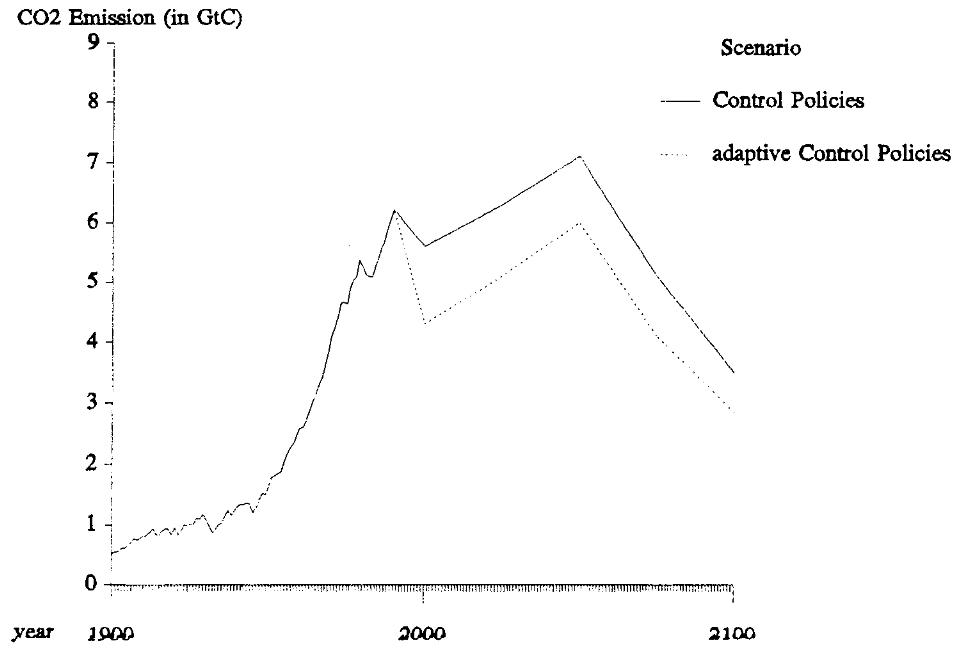

Figure 5.3: Adapted and original emission-scenario.

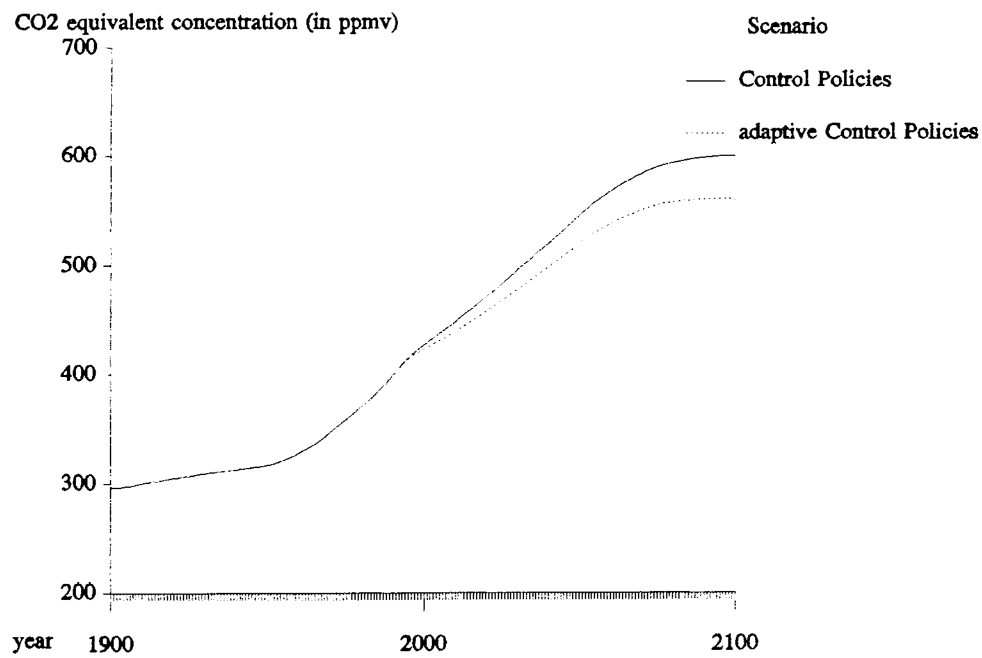

Figure 5.4 Concentration paths of original and adapted scenario.

5.3 Regional Allocation

5.3.1 Cost Minimization

5.3.1.1 Reference Case

Here we try to minimize the cost of reducing the CO_2-emissions under the constraint of achieving a climate target (see section 4.3.2.). In the reference case, minimizing cost results in a reduction of global emissions of 20 percent till 2000 and 30 percent till 2100 relative to present emissions. The fast reductions in the beginning are caused by the fact that the rate of reducing cost by technical improvement is not large enough to delay reductions. The reductions and their cost are mostly allocated in the OECD and FCP regions (Figure 5.5 and 5.6), which is caused by the assumption that reductions are relatively more cost efficient in regions with high emissions per capita (see section 4.3.2). In these regions the CO_2-emissions have to decline with an average rate of 3 percent annually in the first ten years and about 0.2 percent annually in the next century. The emissions are not significantly reduced in developing regions (low emission per capita).
Using a simple relation between GNP and carbon emissions (see section 4.3.3), we can estimate the regional and global GNP for the next century. The global GNP decreases somewhat in the beginning of the period due to sharp emission reductions in developed regions, but the average annual growth rate in the whole period is about 1 percent, which is even lower than 1.6% of the IPCC's Lower economic growth case (IPCC, 1991). This difference can be explained by the fact that we have neglected coal intensity improvements by changes in the fuel mix. The growth rate varies between 0.7% and 1.4% in OECD regions, between 0.8 and 1.2% in FCP regions and between 1.3% an 1.4% in developing regions (Figure 5.7).
Differences in population growth cause differences in the growth rates of GNP per capita. In OECD regions GNP per capita increased with an average annual rate between 0.6% and 1.2%, in FCP regions with a rate between 0.6% and 1.1% and in developing regions with a rate between -0.1% and 0.9%. These GNP per capita rates cause an increase of utility for almost all regions (Figure 5.8), but the large regional differences still remain.
Using the regional emission paths, we can estimate the emission debt of fossil fuel combustion for the individual regions. Emission debt keeps increasing in OECD and FCP regions (Figure 5.9), while the credits remain increasing in the developing regions. Because no account of past emissions is made when cost is minimized, the debt of developed regions remains growing.

- *Minimizing cost leads to an immediately reduction of 20% till 2000, which have to be realized by OECD and FCP regions.*

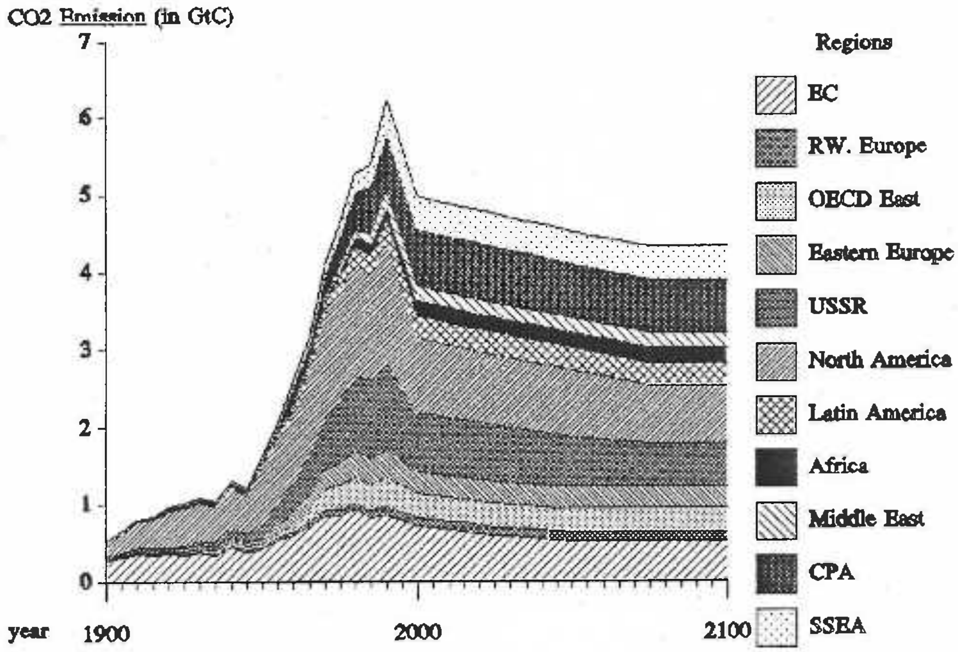

Figure 5.5: Regional carbon emissions when cost are minimized.

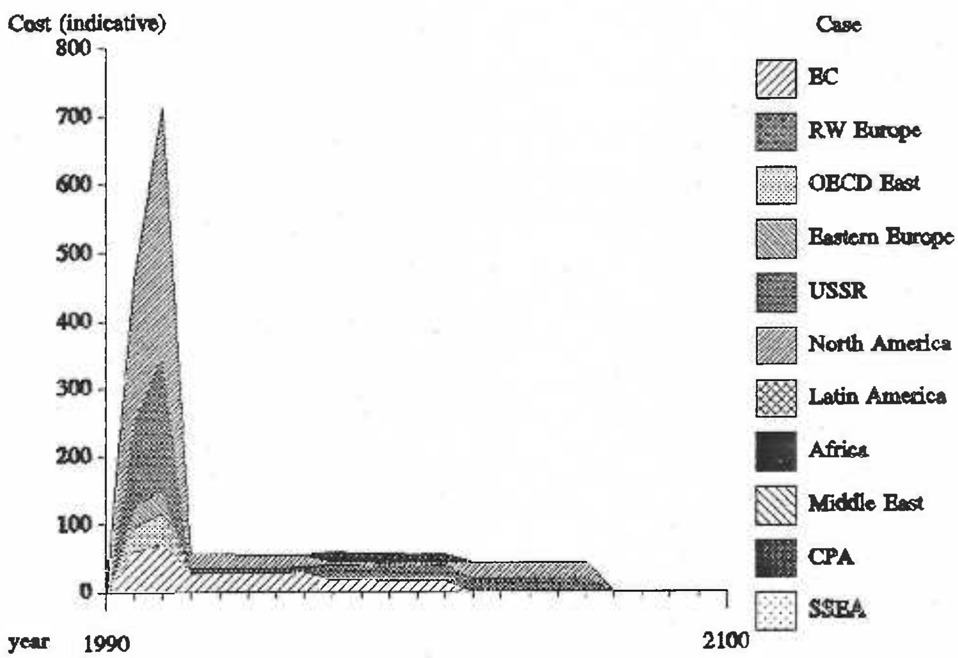

Figure 5.6: Regional cost when cost are minimized.

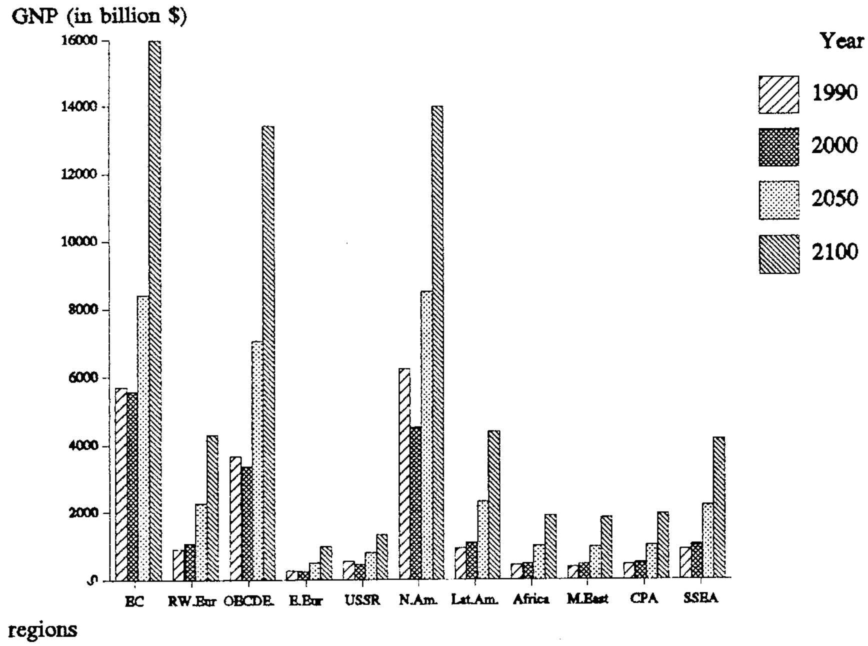

Figure 5.7: Regional GNP in billion dollars for different timepoints.

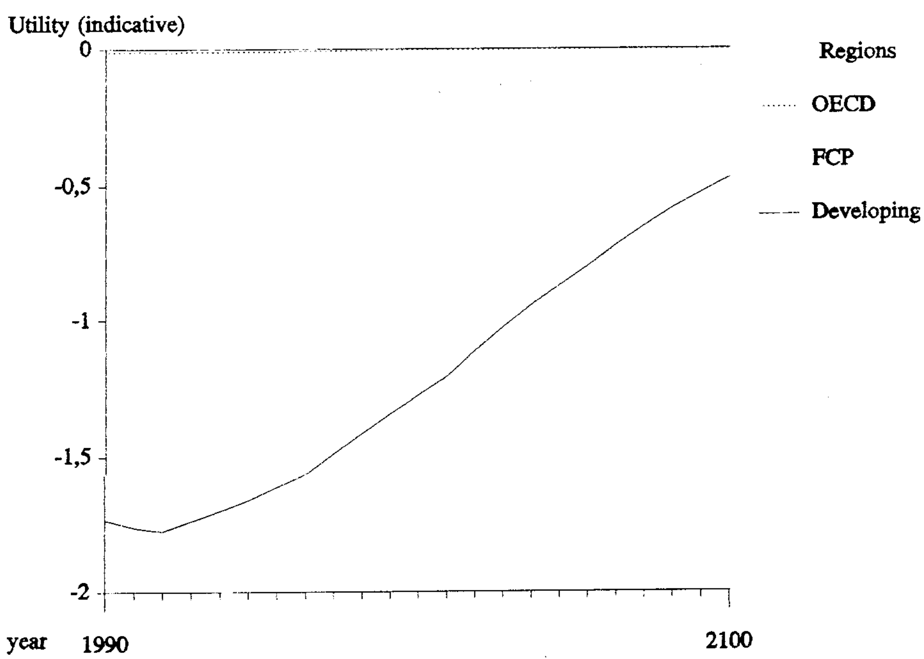

Figure 5.8: Regional utility per capita values when cost are minimized. Utility of OECD regions are not significantly different from the upper level.

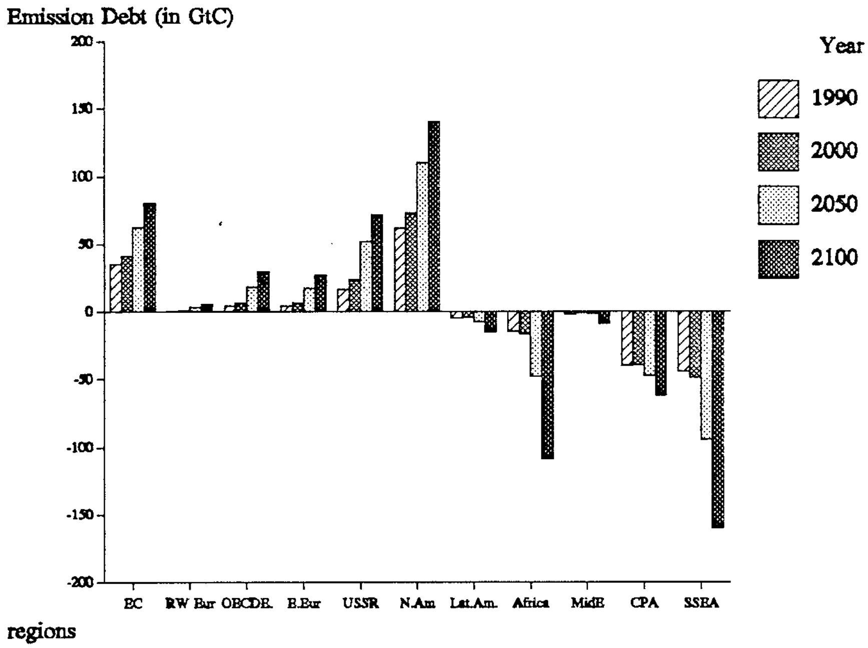

Figure 5.9: Regional emission debt in GtC for different points in time.

5.3.1.2 Case Studies

1. Changing energy intensity improvement rate

In this subsection we study the effect of higher and lower rates of energy intensity improvements. The reduction cost in the future is assumed to be dependent of the rate of technical improvement, which is assumed to have the same rate as the energy intensity improvement. Using the highest rates of the high efficiency case (from 2.5% in 1990 to 1.8% in 2100) and the lowest rates of the moderate efficiency case (from 1.0% in 1990 and 0.7% in 2100) (IPCC, 1991) as bounds of uncertainty, cost is minimized for both cases .
When energy intensity improvement is high, 9% emission reductions till 2000 and 34% till 2100 are necessary on global scale (Table 5.1). Higher technical improvement reduces cost of future reductions in such an amount that the reductions are for a part delayed and the total cost is 3 percent lower than for the reference case. Utility per capita of the average individual is significantly higher than the reference case because GNP is derived in a less energy intensive economy.
When technical improvement is low, global emissions have to be reduced with 26% till 2000 and 29% till 2100, which causes an increase in total cost of 10% (Figure 5.9). The low improvement rate causes a low growth of GNP per capita and therefore just a low increase of utility of the average individual.

- *Higher technical improvement causes a small delay of necessary reductions, lower cost and a significant higher utility per capita compared with the reference case.*

2. Discounting future cost

When risks and benefits are weighted there is a tendency to opt for near term gratification rather than long term rewards, which is especially strong when dealing with benefits to be reaped by future generations (Kellogg and Schware, 1981). To study the effect of discounting future cost, we use a discount factor of 5%, which is frequently used (James, 1989).
The global reductions remain on the present level till 2025, followed by a reduction of 58% till 2100 (Table 5.1). Now also reductions are needed in developing regions to reach the climate target. The large reductions causes a 50% higher total (non-discounted) cost than the reference case.
Avoiding emission reductions in this century causes a little rise of utility in this period in developed regions. However, because large emission reductions in the middle of the next century in developing regions reduce GNP growth in those regions, utility per capita declines in the next century.

- *Discounting future cost causes a delay of measures and leads to higher welfare and less cost of present population in OECD and FCP regions, but leads also to significantly higher cost and smaller welfare for future population especially in developing regions.*

3. Changing climate targets

The concentration stabilization target is not strict enough to reach a sustainable development of ecological systems. Therefore we examine the other climate targets, where the energy improvement rate is adapted and the scenarios of non-CO_2 gases follow the target dependent scenarios. The energy intensity rate is assumed to have the highest rate for the relative temperate target (from 2.5% in 1990 to 1.8% in 2100, according to the highest rate of the High Efficiency case of the IPCC (1991)), and to be in between the rate of the reference case and the rate of the relative temperature target for the absolute temperature case.
The global emissions have to be reduced with 30% till 2000 and 40% till 2100 to meet the absolute temperature target. The cost increase with 100% while the average utility per capita decreases in the beginning of the period, mainly caused by reduction in developing regions to meet the climate target, followed by an increase, which ends up higher than the present utility.
To meet the relative temperature target a reduction of global carbon emissions of 40% till 2000 and 55% till 2100 is necessary (Table 5.1). This causes an increase of the reduction cost with 230%, while the average utility per capita decreases first and afterwards it increases above present level.

- *Reducing emissions to sustainable climate targets leads to higher reductions, also in developing regions, and higher cost. Besides, the average utility per capita will first somewhat decline, whereafter it increases above present level.*

4. Changing policy non-CO_2 gases

In the reference case we have assumed that the non-CO_2 gases follow the Control Policy scenario. To estimate the sensitivity of the optimal regional allocation of carbon reductions of non-CO_2 gases we optimize the problem also with the Business-as-Usual scenario. When non-CO_2 gases remain uncontrolled, an immediate reduction of 85 percent of CO_2 emissions is necessary (Table 5.1), which increases the cost with 10000%.
Because of the high reductions also reductions in developing regions are necessary. This is the main cause of the sharp decrease of the average utility in the beginning of the period. Utility per capita will increase after this decline, because of energy intensity improvements, but will not reach present level.

- *When emissions of non-CO_2 gases remain uncontrolled, high reductions (85 %) of CO_2 emissions are necessary to meet the concentration stabilization target. This causes a sharp decline of individual welfare in the beginning of the period and increases the cost with about 10000 %*

Table 5.1: CO_2 emissions in industrialized regions (OECD and FCP) and developing regions (DEV) when cost is minimized for different cases (in GtC).

Case	1990	2000	2025	2050	2075	2100
Reference						
OECD	2.9	2.1	1.9	1.8	1.7	1.7
FCP	1.5	1.1	1.0	0.9	0.8	0.8
DEV	1.8	1.8	1.8	1.8	1.8	1.8
Global	6.2	5.0	4.7	4.5	4.3	4.3
1. High Improvement						
OECD	2.9	2.5	1.9	1.7	1.5	1.3
FCP	1.5	1.3	1.0	0.9	0.8	0.8
DEV	1.8	1.8	1.8	1.8	1.8	1.8
Global	6.2	5.7	4.8	4.4	4.1	4.1
Low Improvement						
OECD	2.9	1.8	1.8	1.8	1.7	1.7
FCP	1.5	1.0	1.0	1.0	1.0	1.0
DEV	1.8	1.8	1.8	1.8	1.8	1.8
Global	6.2	4.6	4.6	4.5	4.4	4.4
2. Discounting						
OECD	2.9	2.9	2.9	2.2	1.2	0.8
FCP	1.5	1.5	1.5	1.2	0.5	0.4
DEV	1.8	1.8	1.8	1.8	1.4	1.4
Global	6.2	6.2	6.2	5.2	3.1	2.6
3.Absolute Temperature Target						
OECD	2.9	1.7	1.6	1.4	1.3	1.3
FCP	1.5	0.9	0.8	0.7	0.7	0.7
DEV	1.8	1.7	1.7	1.7	1.7	1.7
Global	6.2	4.3	4.1	3.8	3.6	3.6
Relative Temperature Target						
OECD	2.9	1.4	1.3	1.1	1.0	1.0
FCP	1.5	0.7	0.7	0.6	0.5	0.5
DEV	1.8	1.5	1.5	1.4	1.3	1.3
Global	6.2	3.7	3.5	3.0	2.7	2.7
4. Uncontrolled non-CO_2 Gases						
OECD	2.9	0.4	0.2	0.2	0.2	0.2
FCP	1.5	0.1	0.1	0.1	0.1	0.1
DEV	1.8	0.3	0.3	0.3	0.3	0.3
Global	6.2	0.9	0.7	0.7	0.7	0.7

5.2.3 Utility Maximization

5.2.3.1 Reference Case

In this section results are given of allocations of regional CO_2 emissions by fossil fuel combustion, which maximize total utility for the future population. The analytical utility function, which is discussed in section 4.3.3 is dependent of the elasticity of the marginal utility and GNP per capita. The influence of the elasticity of the marginal utility was given in section 4.3.3. In the reference case we use an elasticity of 2.5. The annual change of GNP is restricted between 0 percent and 6 percent growth. This upperbound is higher than the yearly regional GNP prospects as used by the IPCC (1991).
When utility is maximized the global emissions increase with 3% till 2000 followed by a reduction of 50% till 2100 (Figure 5.10). Regional emissions have to be reduced in OECD regions with 18% till 2000 and with 79% till 2100 and in FCP regions with 13% till 2000 and 78% till 2100. In Middle East the emissions have to be reduce with 2% till 2000 and 29% till 2100, while in Latin America emissions are allowed to increase with 13% till 2000 followed by a reduction to 50 percent of the present emission level in 2100. Emissions in Africa are allowed to increase with 310% till 2050 followed by a decline to an emission level in 2100 of 270% above present emission. The same happens in CPA and South/Southeast Asia, where emissions are allowed to increase with respectively 59% till 2025 and 194% till 2050, followed by a decline to an emission level in 2100 of 0% and 58% above present emissions. The regional differences are caused by differences in GNP per capita. However, the reductions in OECD and FCP regions are restricted by the GNP restriction, while the increase in Africa and Asia regions is restricted by the concentration restriction. The continuing reductions in developed regions results in high reduction cost over the whole period (Figure 5.11).
The global GNP (dependent of carbon emissions (see 4.3.3)) increases with an average annual rate 0.5[1] percent. The GNP in developing regions increases with an average annual rate between 0.7 and 2.3%, while GNP in developed regions stays on the same level (Figure 5.12). GNP per capita decreases with an average annual rate between 0.4 and -0.1% in developed regions, 0% in Latin America, 0.3% in the Middle East, but increases with a rate between 0.8 and 1.1 percent in Asia and Africa. Therefore, utility per capita, dependent of GNP per capita, increases with large rate in Africa and Asia, but declines a little in other regions (Figure 5.13). Although the average GNP declines with almost 0.2 percent a year, the average utility per capita increases because GNP is more equally divided over the regions. However, the utility level of the OECD regions remains significant higher than other regions. Emission debt of fossil fuel combustion (see chapter 3) can be estimated using the regional emission paths (Figure 5.14). The restriction that GNP is not allowed to decline, results in growing debts in most of the developed regions and growing credits in most of the developing regions. Only in region Rest of Western Europe debt will reduce and in Centrally Planned Asia credits will decline.

- *When total utility of the future population is maximized emissions in developing regions are allowed to increase while industrialized regions have to reduce their emissions with large amounts (up to 80% in 2100).*

[1] Lower than the growth rates as used by the IPCC (1991) (see 5.2.2).

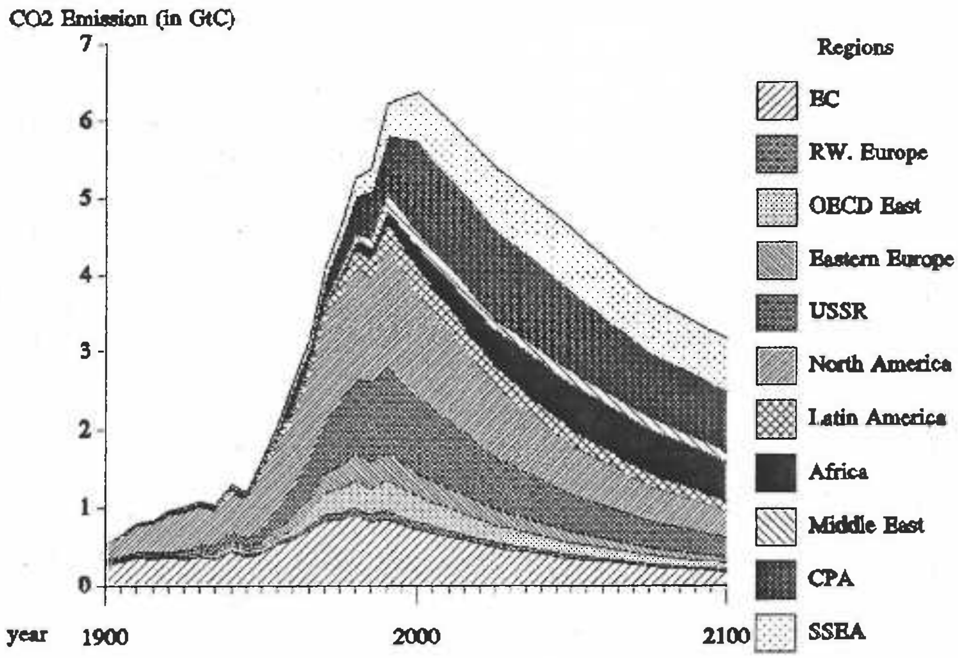

Figure 5.10: Regional emissions when utility is maximized.

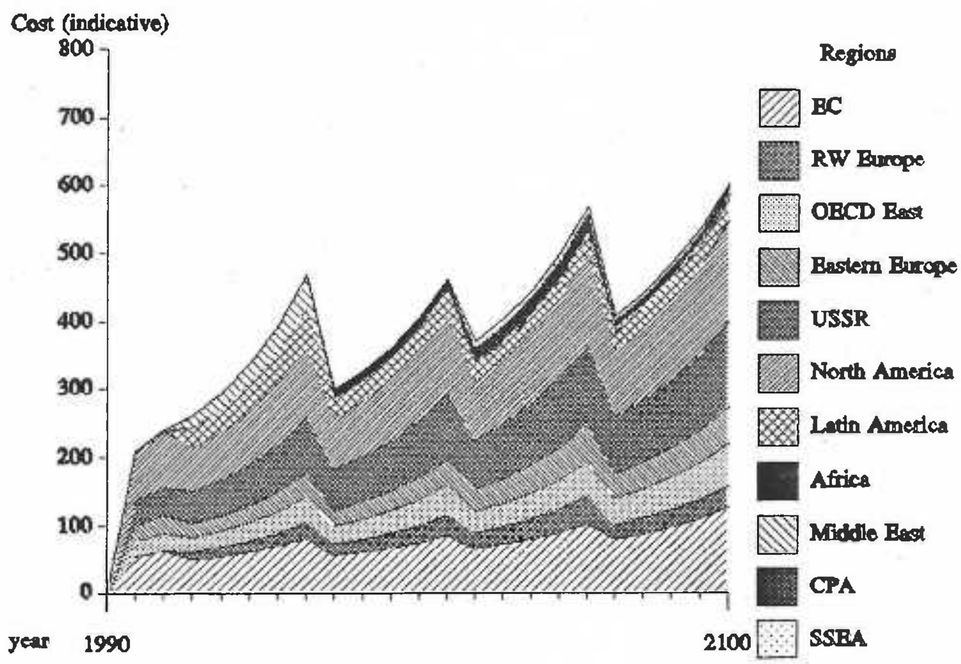

Figure 5.11: Regional cost paths when utility is maximized. The time period of 25 years between the decision variables determines the form, while the periods inbetween have a fixed reduction rate.

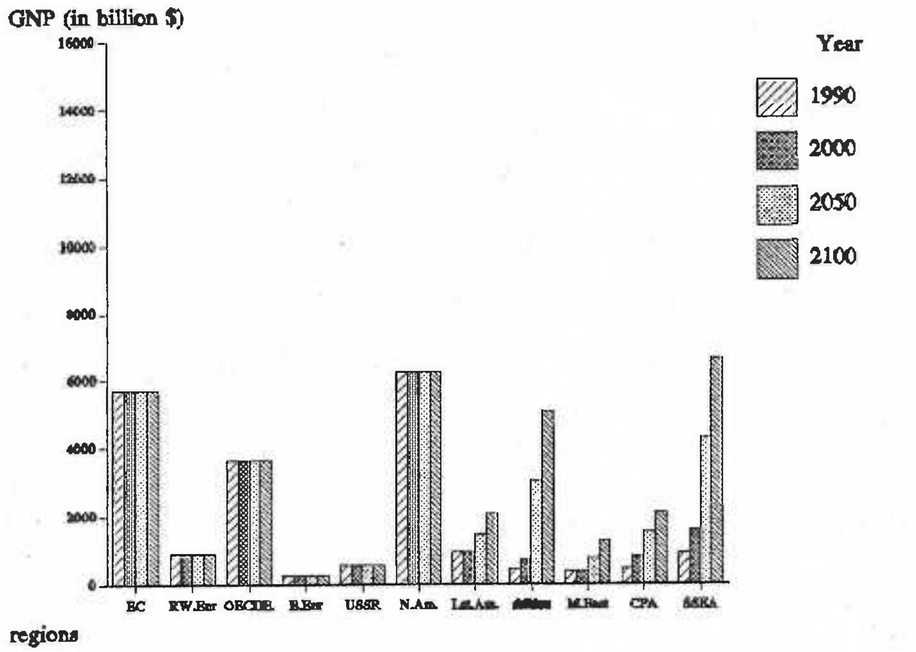

Figure 5.12: Regional GNP values in billion dollars when utility is maximized.

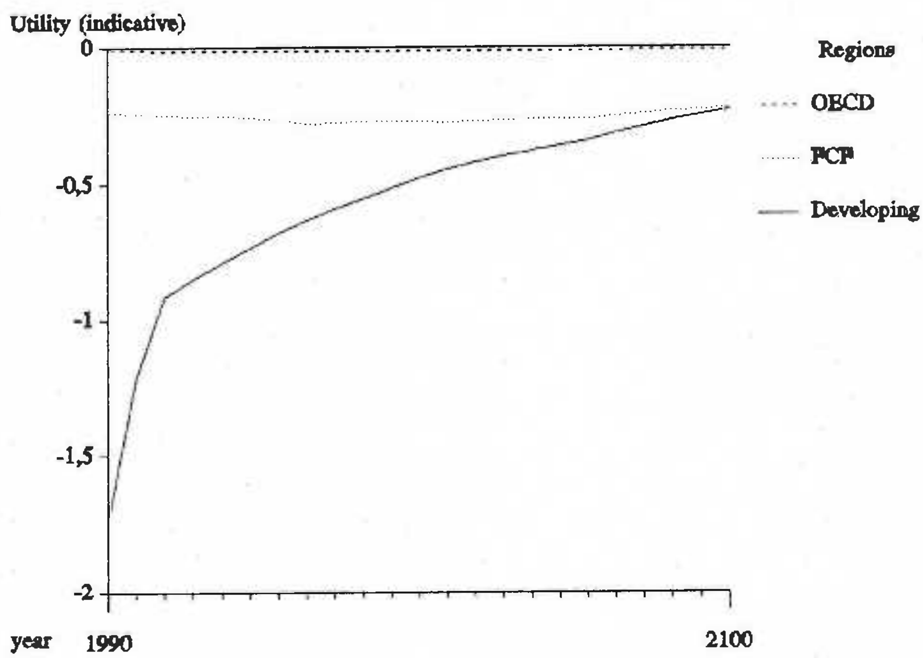

Figure 5.13: Utility per capita when utility is maximized. Utility per capita in OECD regions is not significantly different from the upperlevel.

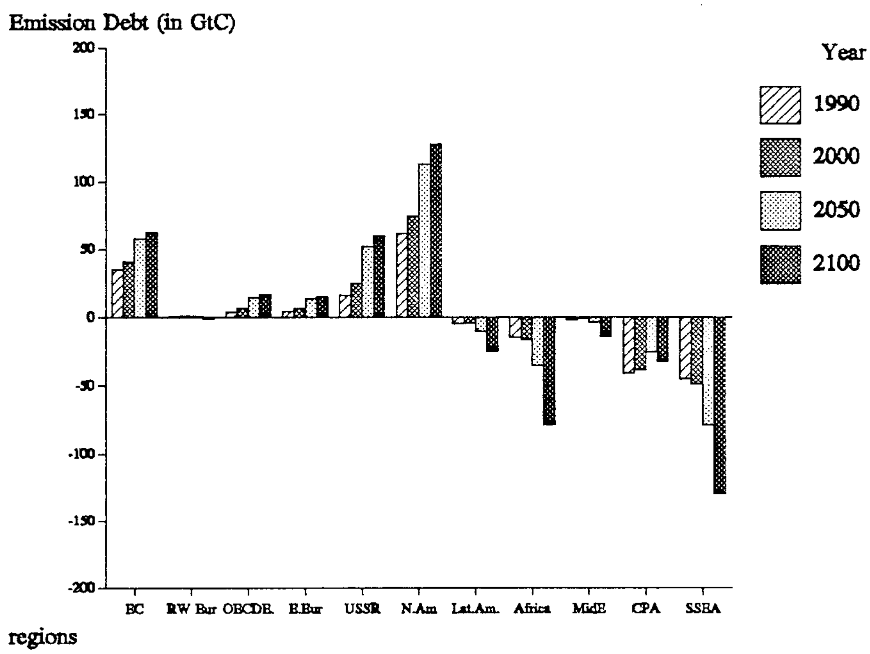

Figure 5.14: Regional emission debt in GtC when utility is maximized.

5.2.3.2 Case Studies

1. Changing energy intensity improvement

In this case we study the sensitivity of improvements of energy intensity. GNP is assumed to be dependent of the energy intensity improvement rate (section 4.3.3). Using the high and low improvement rates (Low: from 1.0% in 1990 to 0.7% in 2100, High: from 2.5% in 1990 to 1.8% in 2100; IPCC, 1991), utility is maximized for both cases.
Global emissions are reduced with 6% till 2000 and 45% till 2100 when there is a high energy intensity improvement. This is caused by large reductions of emissions in OECD and FCP regions (Table 5.2). These larger reductions than the reference case lead to an increase of reduction cost of 40 percent. The increase of emissions in developing regions is larger than in the reference case. This cause a higher average utility per capita level than in the reference case.
Low energy intensity improvement cause lesser reductions in industrialized regions (Table 5.2), and thus restricts the growth possibilities in developing regions. The cost is about 30 percent lower than the reference case due to smaller reductions in developed regions. The resulting utility per capita values are lower than in the reference case, caused by smaller increases or even reductions of emissions in developing regions.

- *Higher energy intensity improvements lead to higher utility but also to higher cost due to larger emission reductions in developed regions.*

2. Changing elasticity of the marginal utility

We will now consider the effect of the elasticity of the marginal utility. Elasticity of marginal utility determines the measure of equity (section 4.3.3). We have maximized utility of two cases: using a high (e=4) and a low (e=2) elasticity.
Different elasticities lead to the same emission levels in developed regions (due to the GNP restriction), but the paths differ in the allocation in time of emission permits in developing regions. Higher elasticity (high measure of equity) leads to higher emission permits in the beginning of the period in the poorest regions (Table 5.2), in contrary to low elasticity where emission permits are delayed compared with the reference case. The costs between the cases are not significantly different.

- *Maximizing utility with high elasticity (high measure of equity) will raise utility as fast as possible, which results in higher carbon emissions in the poorest regions in the beginning of the period.*

3. Changing economic constraints

The solutions are strongly determined by the lowerbound restriction on the change of GNP, because developed regions reduce their emissions to the underbound restriction in the reference case (constant GNP). Therefore we have maximized utility with higher and lower allowed reductions of GNP growth. When the GNP is restricted to increase at least 1 percent a year over the whole period for all regions, no feasible solution is found. However, when a decrease of 1 percent is allowed the utility increases significantly because of more carbon emissions are allocated in developing regions (12% more in 2100). However the cost is about four times higher than the reference case, because of the large reductions in developed regions.

- *The solutions of utility maximization are highly sensitive for changes in the GNP restriction.*

4. Changing climate targets

We will examine the reference case with other climate targets and we adapt the energy intensity improvement rate in the same way as done in the case studies of cost minimizing.
The global emissions have to be reduced with 6% till 2000 and 60% till 2100, to meet the absolute temperature target. The cost of reduction increases with 20%, while the average utility per capita declines compared with the concentration stabilization target, because of lesser emission permits in developing regions. These lesser emission permits are caused by the fact that reductions in industrialized regions are restricted by the GNP restriction and higher reductions are necessary to meet the absolute temperature target.
To meet the relative temperature target, a reduction of 3% till 2000 and 72% till 2100 is needed. The reduction cost increase with about 130% compared with the reference case, while the average utility per capita is lower than in the reference case, because less emissions are allocated in developing regions.

- *To meet sustainable climate targets, larger reductions are necessary. Because of the GNP restrictions, most of these extra reductions reduce the increased emission permits (compared with the reference case) to meet the targets. The reduction cost will increase, while the average utility per capita declines over the whole period.*

5. Changing emissions of other gases

To estimate the influence of changing policy of controlling other trace gases, we maximized utility also with the Business-as-Usual scenario. However no feasible solution is found.

- *When non-CO_2 gases remain uncontrolled, economic growth have to be negative or energy intensity improvements have to be larger to reach the climate targets.*

Table 5.2: CO_2 emissions in industrialized regions (OECD and FCP) and developing regions (DEV) when utility is maximized for different cases (in GtC).

Case	1990	2000	2025	2050	2075	2100
Reference						
OECD	2.9	2.5	1.7	1.2	0.9	0.6
FCP	1.5	1.3	0.9	0.6	0.4	0.3
DEV	1.8	2.6	2.8	2.8	2.4	2.2
Global	6.2	6.4	5.4	4.6	3.7	3.2
1. High Improvement						
OECD	2.9	2.3	1.3	0.8	0.5	0.3
FCP	1.5	1.2	0.7	0.4	0.3	0.2
DEV	1.8	2.3	3.8	3.3	3.0	2.8
Global	6.2	5.8	5.7	4.4	3.7	3.4
Low Improvement						
OECD	2.9	2.6	2.1	1.7	1.4	1.1
FCP	1.5	1.4	1.1	0.9	0.7	0.6
DEV	1.8	2.2	2.1	1.9	1.8	1.7
Global	6.2	6.2	5.3	4.5	3.9	3.4
2. High Elasticity						
OECD	2.9	2.5	1.7	1.2	0.9	0.6
FCP	1.5	1.3	0.9	0.6	0.4	0.3
DEV	1.8	2.6	3.2	2.8	2.3	1.9
Global	6.2	6.4	5.8	4.6	3.6	2.9
Low Elasticity						
OECD	2.9	2.5	1.7	1.2	0.9	0.6
FCP	1.5	1.3	0.9	0.6	0.4	0.3
DEV	1.8	2.2	2.9	2.9	2.7	2.3
Global	6.2	6.0	5.5	4.7	4.0	3.2
3. GNP Growth > -1 %/yr						
OECD	2.9	2.2	1.2	0.6	0.4	0.2
FCP	1.5	1.2	0.6	0.4	0.3	0.3
DEV	1.8	2.3	3.4	3.7	3.2	2.2
Global	6.2	5.7	5.2	4.7	3.9	2.7
4. Absolute Temperature Target						
OECD	2.9	2.5	1.7	1.2	0.9	0.6
FCP	1.5	1.3	0.9	0.6	0.4	0.3
DEV	1.8	2.1	2.3	1.9	1.5	1.7
Global	6.2	5.9	4.9	3.7	2.8	2.6
Relative Temperature Target						
OECD	2.9	2.3	1.3	0.7	0.4	0.3
FCP	1.5	1.2	0.7	0.4	0.2	0.1
DEV	1.8	2.6	2.4	1.7	1.2	1.3
Global	6.2	6.1	4.4	2.8	1.8	1.7

5.3.3 Emission Debt Factor

Historical emissions of fossil fuel combustion still cause some part of the present concentration rise. As discussed in chapter 3 the regional contribution varies. When utility contains an emission debt factor (see section 4.3.3), maximizing utility leads to not significant different global emission paths. The developed regions will have to reduce their emissions with about the same rate as in the reference case, because the GNP change is restricted. The allocation of emission permits in developing regions change somewhat. Regions with large expected population growth profit by accounting of emission debts and credits, while emission credits will increase at the fastest rates in these regions. Especially Africa obtain higher emission permits.
The average utility per capita increases somewhat slower in the beginning of the period, because emissions are more allocated in the poorest regions. The use of the emission debt factor can be compared with a higher elasticity of the marginal utility, because it allocates more emissions in the poorest regions.

- *Using an emission debt factor leads to higher emission permits in developing regions with the largest population growth expectations.*

Table 5.3: Regional carbon budgets for developing regions when utility is maximized with an emission debt factor (in GtC).

weight factor ξ	Latin America	Africa	Middle East	CPA	SSEA
0.0	23.5	53.8	15.9	110.5	80.9
0.001	23.6	55.9	16.2	112.3	82.5
0.01	22.8	63.5	16.5	109.7	81.2

5.3.4 Mixed Forces

Above exercises take either cost minimization or utility maximization as it's goal. A new objective function is constructed, which takes into account both cost minimizing and utility maximization (see section 4.3.4). Using the reference cases of cost minimization and utility maximization and weight both functions equal, a new allocation is derived. The global emissions have to be reduced with 6% till 2000 and 34% till 2100, which values are between the two reference cases (Figure 5.15). The global reductions are first somewhat delayed by increasing emission permits in developing regions, which increase utility. In the beginning of the next century the emissions have to be reduced by more than 20 percent (mainly by industrial regions), which reduce cost, and only declines a little there-after.
The cost and utility values are between the solutions of the reference cases (Figures 5.16 and 5.17). The mixed forces solution follows first the utility maximization solution and then switches to the cost minimization solution as is showed in Figure 5.17. This is mainly caused by the GNP restriction which decreases the allowable reductions and which was not used in the cost minimization case.

- *Mixed objective functions lead to an allocation which takes into account both cost and utility aspects. Using mixed forces could be of both theoretical and practical importance to derive allocations which account of both social and economic aspects.*

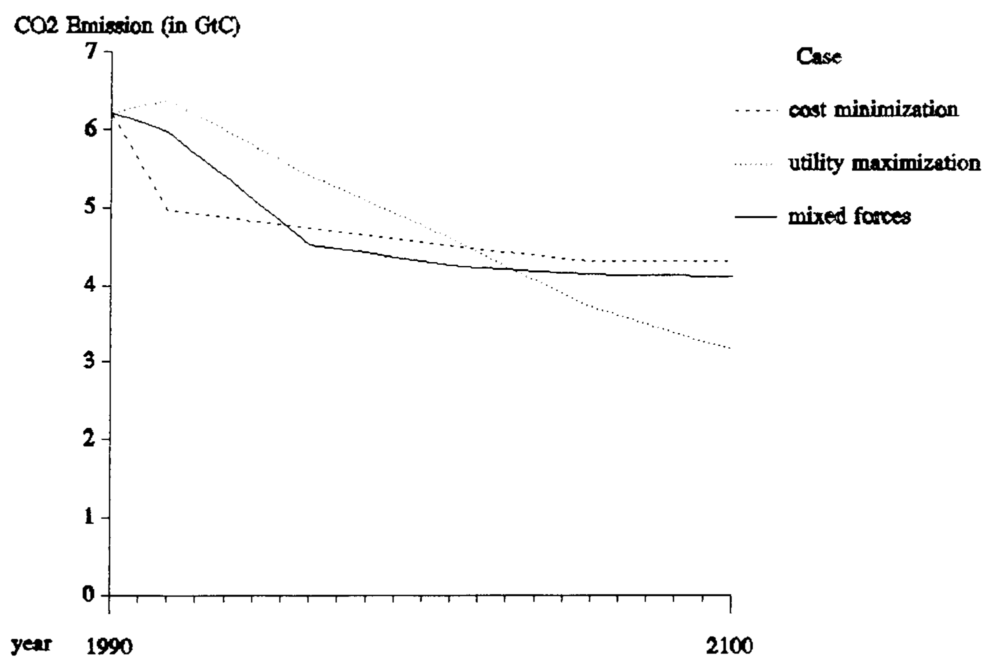

Figure 5.15: Global emissions for the three cases.

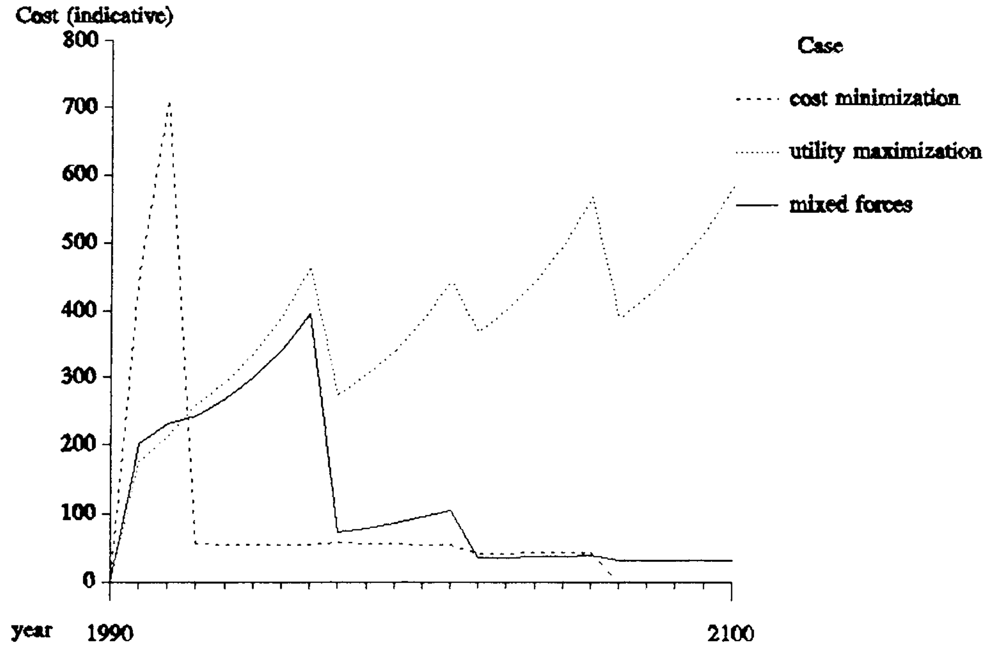

Figure 5.16: Global cost for the different cases.

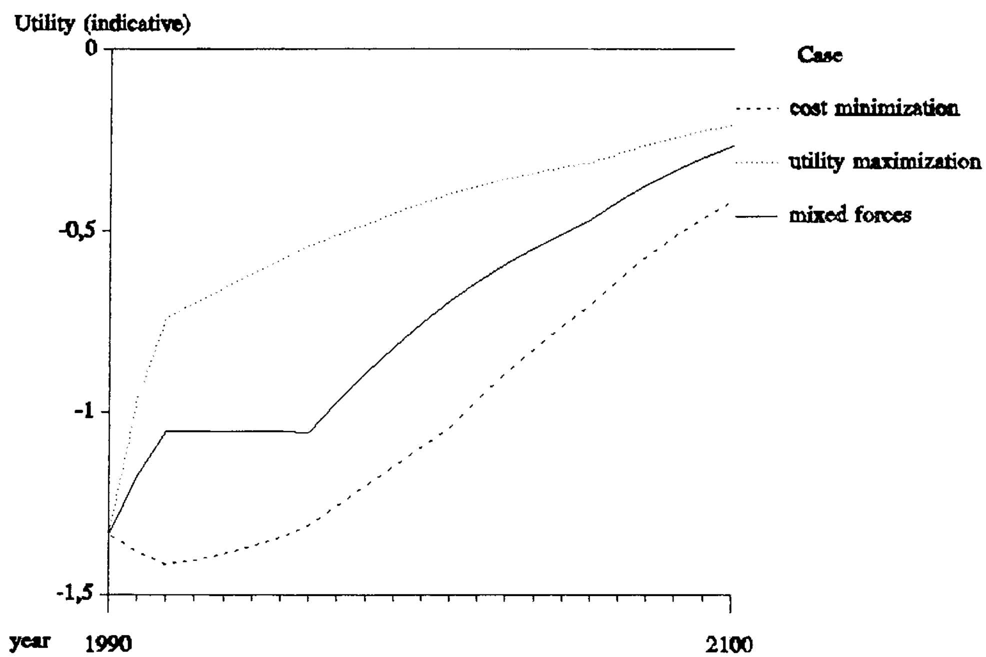

Figure 5.17: Average utility per capita for the different cases.

5.4 Discussion

Solutions of maximizing the carbon budget show that absolute reductions of all greenhouse gases are necessary to meet the climate targets. These reductions will be larger when social and economical aspects are taken into account. Cost minimization leads to immediate large reductions (at least 20% in 2000) in contrary to utility maximization where due to increased emissions in developing regions the global emissions rise till 2000 followed by a sharp decreasing emission path (at least 50% reduction in 2100). The emission reductions are for the most part allocated in developed regions. The advantage of the developing regions due to lesser reductions or even increased emission permits is declined per capita by the large population growth. The reduction cost of the reference case of utility maximization is about four times higher than in the cost minimization case.
GNP growth, dependent of carbon emissions, is larger with cost minimization because with utility maximization emissions are more allocated in regions where GNP has a higher carbon intensity. Utility of the average person, dependent of GNP per capita, increases in time and this increase is larger with utility maximizing. However, the large difference between OECD regions and other regions remains in all cases. This also holds for the increasing emission debts of developed regions.
When non-CO_2 gases remain uncontrolled, reduction cost will rise with a large amount to meet the concentration stabilization target. To meet sustainable climate targets large reductions have to be made which lead to higher cost. Energy improvements have little impact on the global emission path, but a large impact on the distribution between regions, and on the average utility per capita.
Discounting future cost will lead to higher (non-discounted) cost in the future, especially in developing regions. Using an emission debt factor or a higher level of the marginal elasticity results in higher emission permits in the poorest regions.
Results of mixed forces show that this is an important tool to derive carbon allocations which take into account both economic and social aspects of response policies.
Although the results are derived with rough estimates of objective functions, they show the many possibilities of using optimization techniques in analyzing response strategies.

6 Discussion

It was the objective of this study to develop global climate strategies which meet the sustainable targets in order to minimize the risks of induced climatic change. To allocate the responsibility for future reductions of carbon dioxide among region's, we developed two mechanisms. The first one allocates permitted emission budgets to regions and is based on equatability between the developed and the developing world taking into account the inequities between the historical CO_2-emissions. The second one allocates the CO_2-emissions to regions in time and is based on optimization under a socio-economic impact objective function, like cost and utility.

In the first approach, we analyzed the regional contribution to past atmospheric CO_2-concentration rise. We found that 70% is caused by industrial regions, mainly by fossil fuel combustion, and only 30% by developing regions, mainly caused by deforestation. This clearly shows the inequity between the developed and developing world, which we describe via the concept of emission debt. The emission debt tries to quantify the fact that some regions have emitted more CO_2 than they were allowed to, based on an equitable share of the total carbon budget. In this study we assume an equal carbon budget per capita, meaning each person living between 1800 and 2100 has an allowance to emit an equal emission quota yearly irrespective of the generation he or she belongs to or which country he or she lives in. We used two methods to estimate the equal emission quota.
In the intergenerational approach, each person living between 1800 and 2100 would have an allowance of 0.40 tC yearly to meet the *absolute temperature target* (less than 2 degrees °C increase until 2100). However, we have in the past already emitted more than this equal share, which results in a global emission debt of 190 GtC.
In the global carbon budget approach we consider the atmosphere as a sink which can absorb over the period 1991-2100 only a limited amount of carbon. Accounting of past emissions, every human being has an equal permitted emission of 0.56 tC yearly over the period 1800 till 2100. However, we have emitted in the past about an average value of 0.91 tC per capita per year. The resulting global emission debt of 130 GtC (intergenerational) is for the main part (150 GtC) caused by industrialized regions (interregional), while developing regions still have an emission credit of 20 GtC. Allocating the remaining global carbon budget, which takes account of past emissions, increases the budgets of developing regions in contrary to industrialized regions, where North America and the European Community ends up even with negative budgets. This simple allocation mechanism is a helpful tool to improve the understanding of the regional inequity and the problem of allocating future emission rights.

However, this allocation mechanism does not account of the socio-economic consequences of reductions and the form of future emission paths. Therefore we developed a method to solve a constrained nonlinear optimization problem, where the numerical environmental target restriction is estimated by a simulation model and where the objective function roughly estimates the social and economic consequences of response strategies.
Optimization results indicate that immediately large reductions of at least 20% before 2000, mainly by industrialized regions, are necessary. Utility maximization leads to large reductions in industrialized regions and small to large increased emission permits in developing regions and ends up with a reduction of the global emissions of at least 50% in

2100. The indicative reduction cost is four times higher for the utility maximization case compared with cost minimization, however, emissions are more equal shared. Although the reductions of carbon emissions are allocated mostly in industrialized regions, the difference in utility per capita between industrialized and developing regions remains large. Also the emission debt remains growing in developed regions, while emission credit increases in developing regions.
Results of this study also show that the role of non-CO_2-gases is not to be neglected in any negotiation about future response strategies. Sustainable climate targets will not be reached or with unreasonably reductions of CO_2 emissions when emissions of non-CO_2 gases are not controlled in the same way as CO_2 emissions.
The solutions of developed optimization method are only indicative by using rough estimates of the objective functions. The next step in developing tools for allocating regional emission paths of carbon dioxide is to develop a meta model which describes the complex dynamic relations in economic and energy supply systems and use this for developing objective functions. Also the relation between carbon reductions of fossil fuel combustion and reductions of other trace gases in the energy sector will be a subject of further study.

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Appendix 1 Description of the IPCC-scenarios (IPCC, 1991)

scenario gas: CO_2	Business-As-Usual scenario (BaU 90)	2060 Low Emissions scenario
Energy Supply	Major increase in commercial energy use, mainly by use of fossil fuels (coal) by higher economic growth. Primary energy supply (averaged) increases to 565 EJ by 2025 (1.65%/yr) and to 1205 EJ by 2100 (0.95%/yr).	Primary energy supply reaches (averaged) 412 EJ in 2025 and to 640 EJ in 2100, mainly because of the improvements in energy efficiency.
	Oil and natural gas supplies increase through 2025 and then start to decline by resource constraints. The share of coal increases till 60% in 2100.	Share of primary energy supply by natural gas grows to 22% in 2100, for coal 48%; thus still a major role for the fossil fuels.
Energy Demand	Moderate Efficiency, averaged rate of improvement in energy intensity is about 1%.	High Efficiency, mean rate of improvement in energy intensity is about 1.6%.
Emission	CO_2-emissions due to commercial energy and cement reaches 22.0 GtC/yr in 2100 (360% of present level).	CO_2 emissions due to commercial energy and cement increase (+4.5 GtC/yr or +75% in 2100).
Defores-tation	Deforestation rates is the averaged of moderate case and rapid case; moderate case assumes an increase in tropical deforestation to 15 million ha/yr in 2100, rapid case assumes an exponential increase in tropical deforestation to 34 million ha/yr in 2050 and almost tropical deforestation by 2075.	Reforestation case; deforestation stops in 2025, and about 1000 million ha are reforestated in 2100.
	Net CO_2 emissions double in 2025, and after 2025 these emissions start to decline.	The net CO_2 emissions are negative over period 2000 till 2100, -0.2 GtC in 2100.

scenario gas: CO_2	Control Policies scenario	Accelerated Policies scenario
Energy Supply	Primary energy supply reaches (avearged) 412 EJ in 2025 and to 640 EJ in 2100, mainly because of the improvements in energy efficiency. Non-fossil fuel energy supplies start to play a larger role after 2025, covering 71% of primary energy by 2100.	Energy consuption is primary the same as in the Control Policies scenario, except that the energy use is slightly higher in the mid-century by increased availibility of biomass supplies and their lower costs.
	The share of primary energy provided by fossil fuels decline after 2050, while the non-fossil fuels increase thereafter.	The share of primary energy provided by non-fossil sources increases to 41% in 2025, to 79% by 2100.
Energy Demand	High Efficiency, mean rate of improvement in energy intensity is about 1.6%.	High Efficiency, mean rate of improvement in energy intensity is about 1.6%.
Emission	CO_2 emissions increase till 2050 to 7.1 GtC/yr, and thereafter decreases to 3.5 GtC/yr (60% of present level).	CO_2 emissions decrease in the energy scetor (-3.0 GtC/yr or -50% in 2100).
Defores-tation	Reforestation case; deforestation stops in 2025, and about 1000 million ha are reforestated in 2100.	Reforestation case; deforestation stops in 2025, and about 1000 million ha are reforestated in 2100.
	Net CO_2 emissions are over period 2000 till 2100 negative, -0.2 GtC in 2100.	Net CO_2 emissions are negative over period 2000 till 2100, -0.2 GtC in 2100.

scenario gas: CH_4	Business-As-Usual scenario (BaU 90)	2060 Low Emissions scenario
Energy	Major increase in methane emissions due to increase in energy production of coal and gas (+250 Tg/yr or 300% in 2100).	Methane emissions from energy consumption grow with increasing consumption of coal and gas (+71.5 Tg/yr or 80% in 2100).
Landfills	Methane emissions from waste disposal grow with population and economy (+140 Tg/yr or 350% in 2100).	Methane emissions from land fills grow till 2050, and then start to decline by control technologies till 46 Tg/yr in 2100 (+13% of current level).
Rice	Methane emissions from rice paddies grow with the area harvested (+47 Tg/yr or 45% in 2100).	Methane emissions from rice paddies grow with the area harvested (+47 Tg/yr or 45% in 2100).
Enteric fermen-tation	Methane emissions from cattle grow with an increasing livestock population (+93 Tg/yr or 125% in 2100).	Methane emissions from cattle grow with an increasing livestock population (+93 Tg/yr or 125% in 2100).
gas: CO		
Energy	Carbon monoxide emissions from energy consumption grow with increasing transportation and other energy consuption (+446 Tg/yr or 245% in 2100).	Carbon monoxide emissions from energy consumption and transport decrease by current emission control technologies on mobile and stationary sources (-110 Tg/yr or -60% in 2100).
Defores-tation	Carbon monoxide emissions from deforestation grow with increasing rates of forest destruction (+120 Tg/yr or 90% in 2025), decrease thereafter because forest depletion).	Carbon monoxide emissions from deforestation decrease with decreasing rates of deforestation (-135 Tg/yr or 100% in 2100).

scenario gas: CH_4	Control Policies scenario	Accelerated Policies scenario
Energy	Methane emissions from energy consumption increase (+37 Tg/yr or 46% in 2050), and thereafter decrease due to decreasing energy consumption till 75% of present level in 2100.	Methane emissions from energy consumption grow with increasing energy consumption (+13 Tg/yr or 15% in 2000), decrease thereafter due to decreasing energy consumption till 65% of present level in 2100.
Landfills	Methane emissions from land fills grow till 2050, and then start to decline by control technologies till 46 Tg/yr in 2100 (+13% of current level).	Methane emissions from land fills grow till 2050, and then start to decline by control technologies till 46 Tg/yr in 2100 (+13% of current level).
Rice	Methane emissions from rice paddies decrease after 2050 by altering rice cultivation practices and rice cultivars to 80% of present level.	Methane emissions from rice paddies decrease after 2050 by altering rice cultivation practices and rice cultivars to 80% of present level.
Enteric fermen-tation	Methane emissions from cattle grow controlled by adopting meat and dairy production techniques, till +23 Tg/yr or 30% in 2100.	Methane emissions from cattle grow controlled by adopting meat and dairy production techniques, till +23 Tg/yr or 30% in 2100.
gas: CO		
Energy	Carbon monoxide emissions from energy consumption and transport decrease by current emission control technologies on mobile and stationairy sources and decreasing fossil fuel use (-121 Tg/yr or 65% in 2100).	Carbon monoxide emissions from energy consumption and transport decrease by current emission control technologies on mobile and stationary sources and decreasing energy use (-117 Tg/yr or 63% in 2100).
Defores-tation	Carbon monoxide emissions from deforestation decrease with decreasing rates of deforestation (-135 Tg/yr or 100% in 2100).	Carbon monoxide emissions from deforestation decrease with decreasing rates of deforestation (-135 Tg/yr or 100% in 2100).

scenario	Business-As-Usual scenario	2060 Low Emission scenario
gas: N_2O	(BaU 90)	
Energy	Increase in N_2O emissions from coal use (3.1 Tg/yr or 280% in 2100).	Increase in N_2O emissions related to energy use (0.7 Tg/yr or 64% in 2100).
Fertilizer	Fertilizer use grows by increasing agricultural activities due to the growing population (2.4 Tg/yr or 150% in 2100).	Fertilizer use grows by increasing agricultural activities due to the growing population (2.4 Tg/yr or 150% in 2100).
Biomass burning	N_2O emissions from biomass burning increase till 2050 with 40%, therafter decrease till 90% of present level.	N_2O emissions from biomass burning decrease (-0.5 Tg/yr or -35% in 2100).
gas: halo-carbons		
CFCs and other chemicals	No strengthening of the Montreal Protocol and only 85% participation of the developing countries After 2025, the emissions in non-participating countries mimic further reduction of emissions and cause an almost constant remaining emission level.	No strengthening of the Montreal Protocol and 100% participation.
HCFCs and HFCs	Alternatives, HCFCs and HFCs replace 35% of the phased-out CFCs and grow with 2.5% annually.	Alternatives, HCFCs and HFCs replace 35% of the phased-out CFCs and grow with 2.5% annually.

scenario gas: N_2O	Control Policies scenario	Accelerated Policies scenario
Energy	Increasing N_2O emissions till 2050 to 1.4 Tg/yr, thereafter a decrease till present level.	Increasing N_2O emissions till 2050 to 1.2 Tg/yr, thereafter a decrease till present level.
Fertilizer	N_2O emissions due fertilizer use grows controlled, due to by efforts to control the emissions, such as changing type of fertilizer (+0.6 Tg/yr or +38% in 2100).	N_2O emissions due fertilizer use grows controlled, due to by efforts to control the emissions, such as changing type of fertilizer (+0.6 Tg/yr or +38% in 2100).
Biomass burning	N_2O emissions from biomass burning decrease (-0.5 Tg/yr or -35% in 2100).	N_2O emissions from biomass burning decrease (-0.5 Tg/yr or -35% in 2100).
gas: halo-carbons		
CFCs and other chemicals	Complete phase out of CFCs by the year 2000 and for methyl chloroform and carbon tetra chloride 10 years later.	Complete phase out of CFCs by the year 2000 and for methyl chloroform and carbon tetra chloride 10 years later.
HCFCs and HFCs	Alternatives, HCFCs and HFCs replace 35% of the phased-out CFCs and grow 2.5% annually.	Alternatives, HCFCs and HFCs replace 35% of the phased-out CFCs and grow with 2.5% annually.

Appendix 2 Historical Carbon Emissions

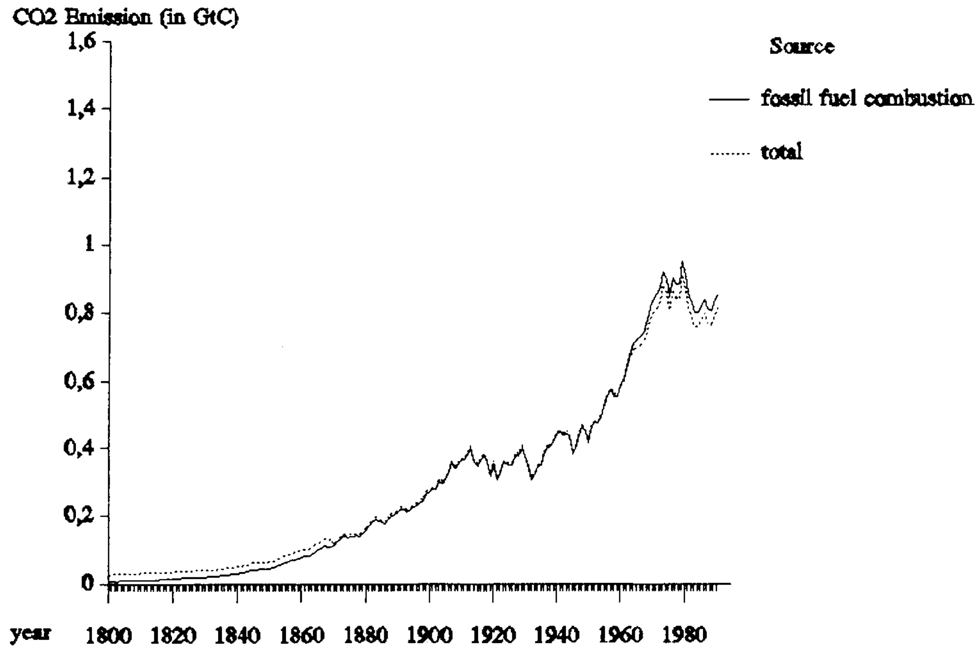

Figure A.2.1: European Community.

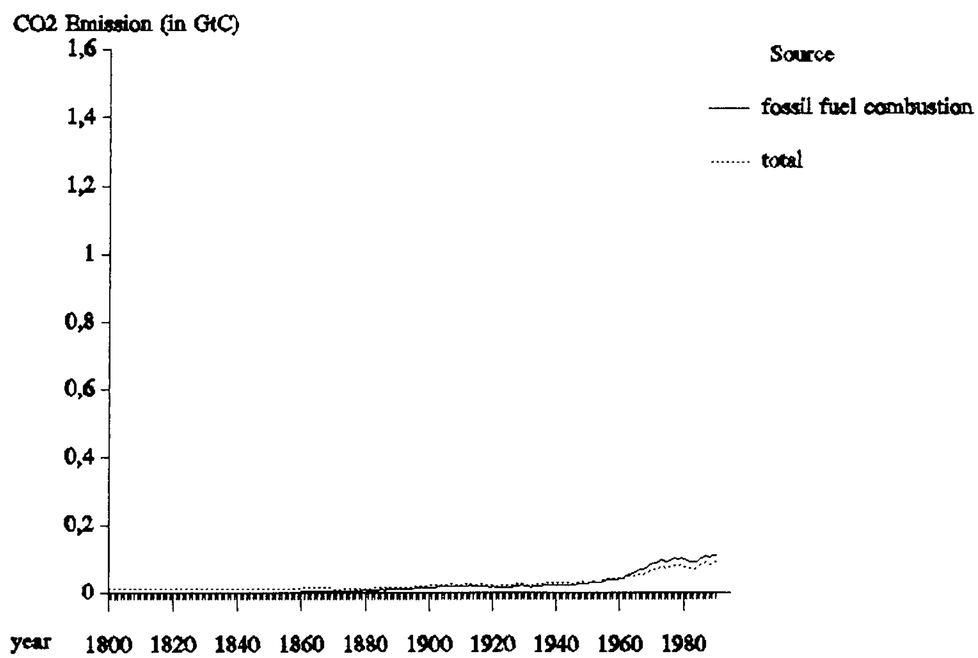

Figure A.2.2: Rest of Western Europe.

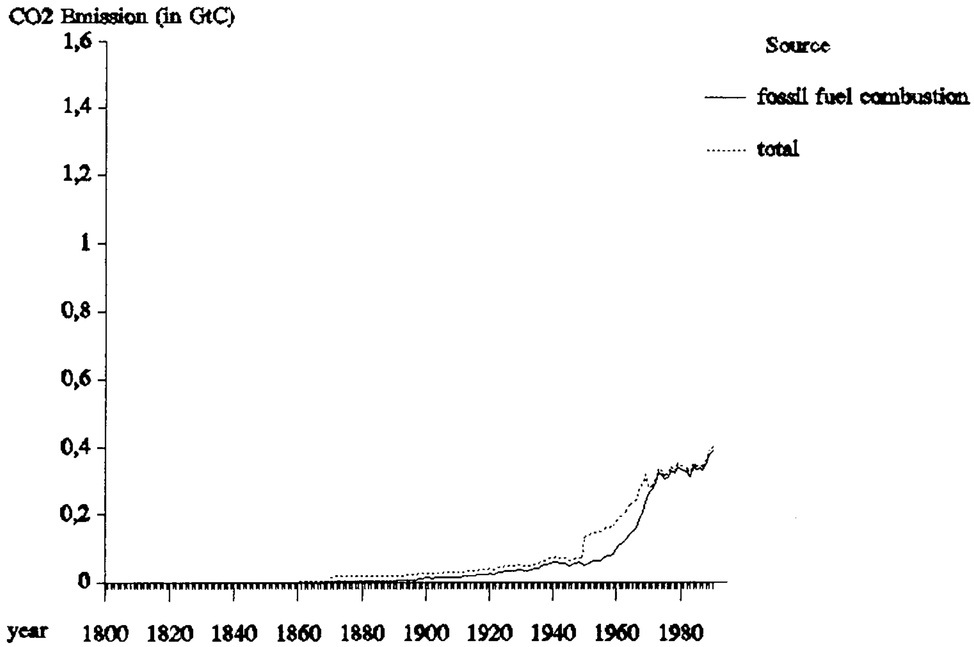

Figure A.2.3: OECD East.

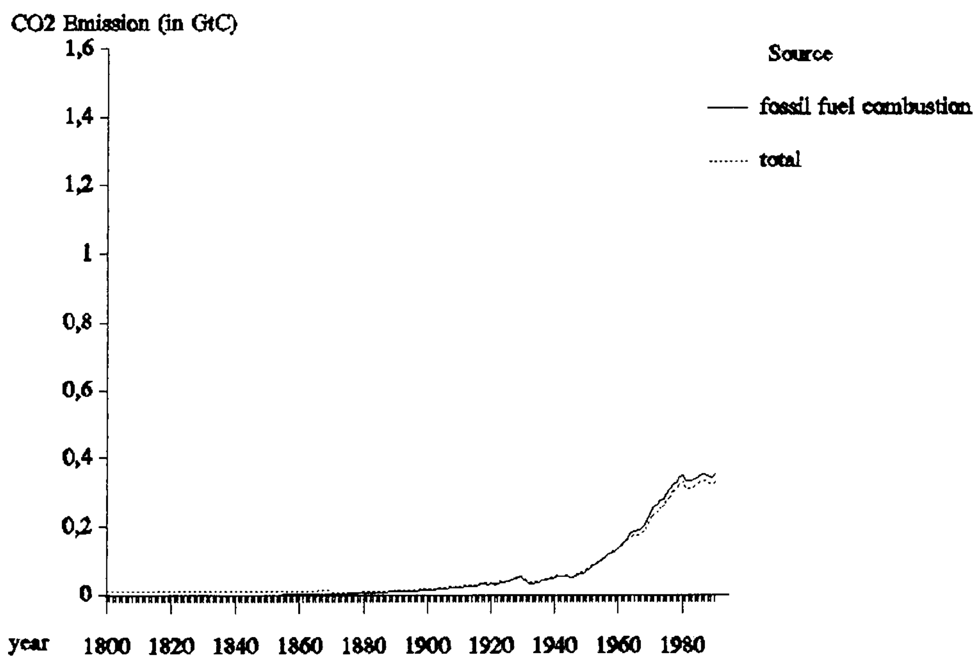

Figure A.2.4: Eastern Europe.

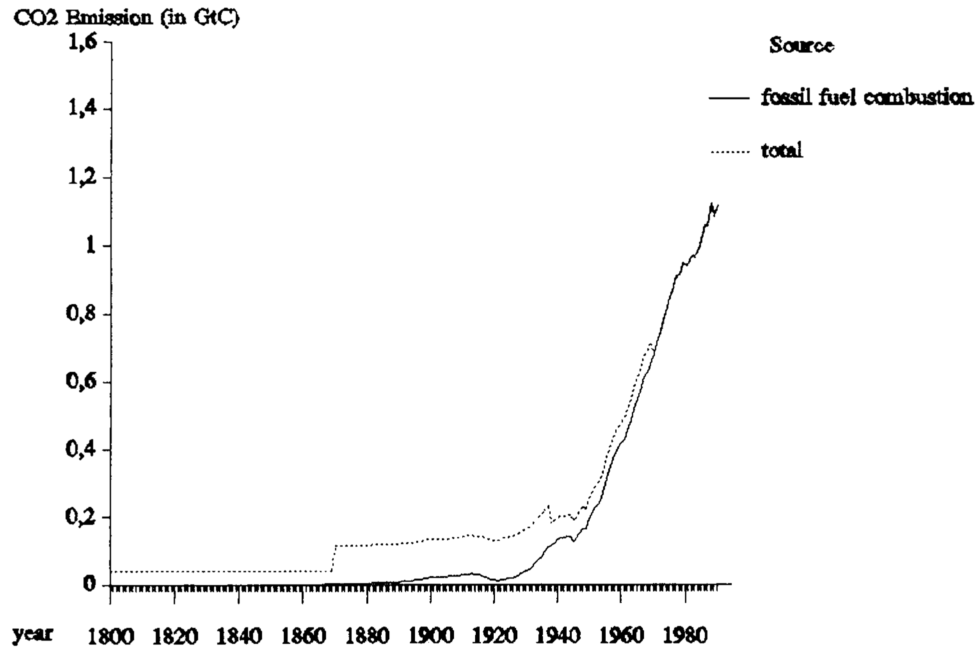

Figure A.2.5: USSR.

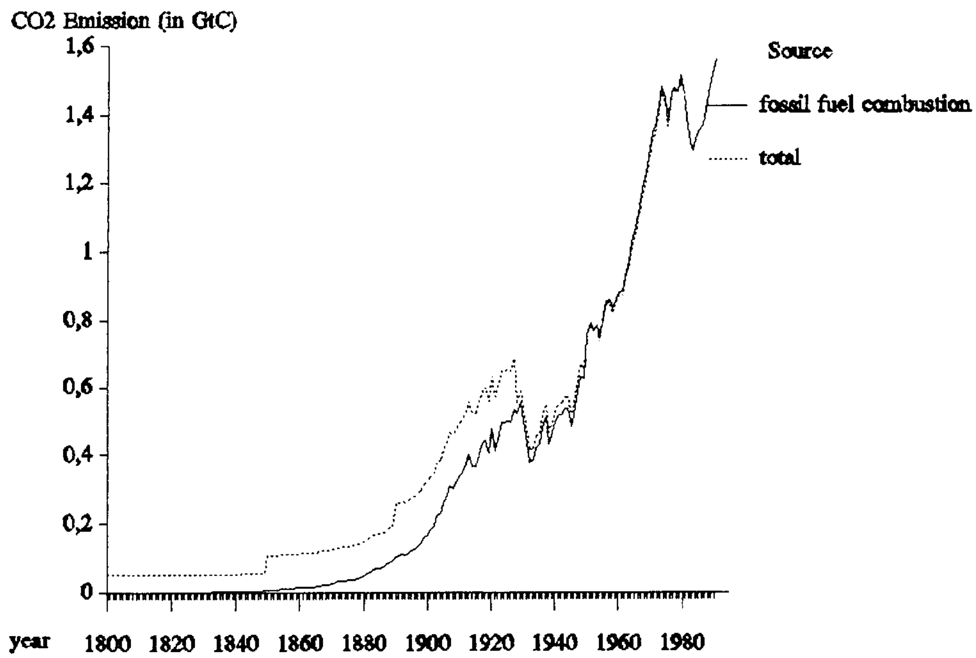

Figure A.2.6: North America.

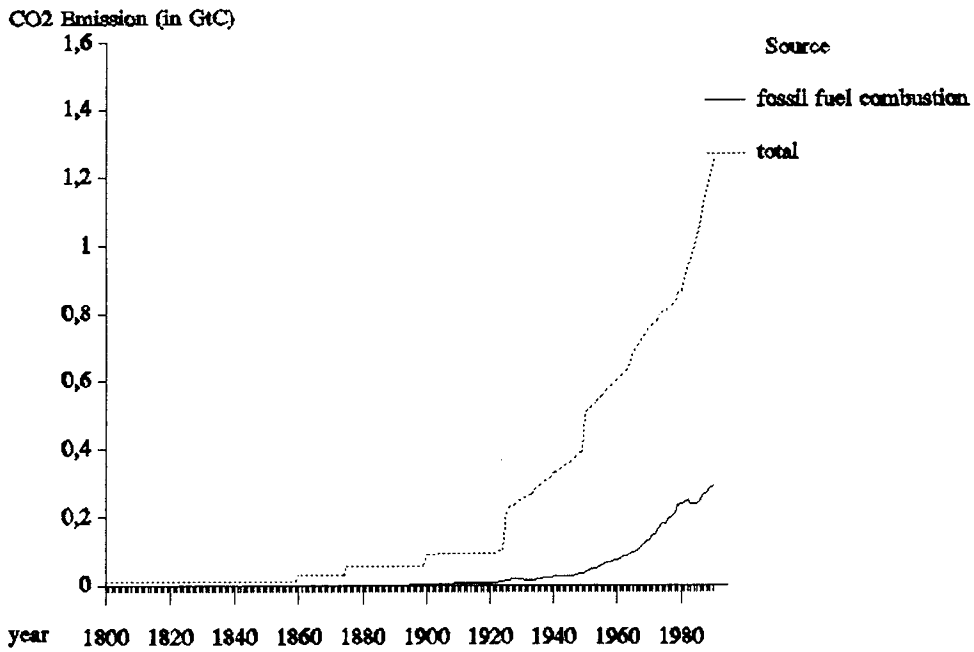

Figure A.2.7: Latin America.

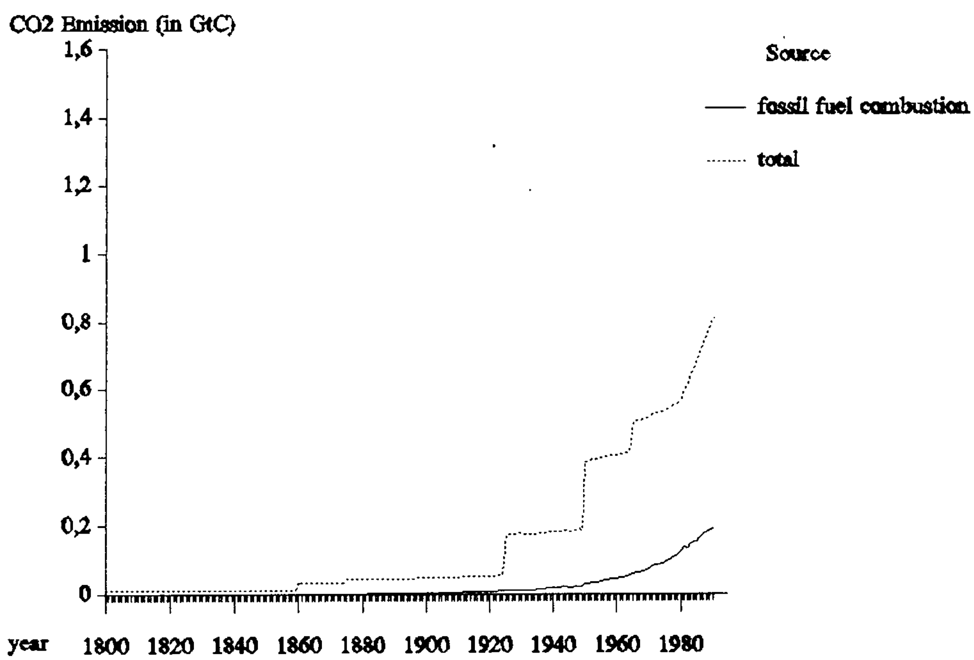

Figure A.2. 8: Africa.

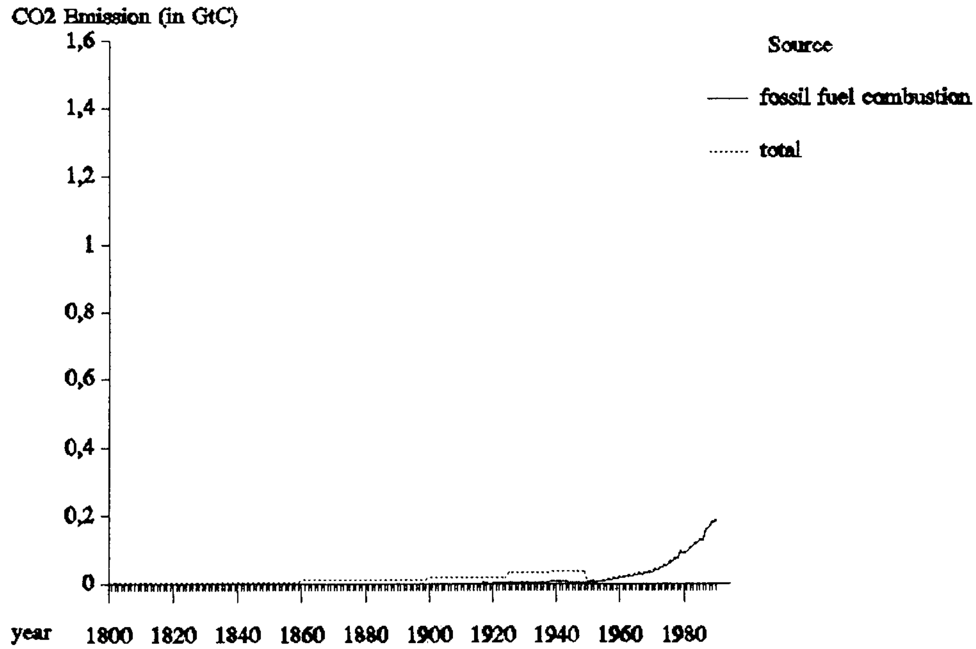

Figure A.2.9: Middle East.

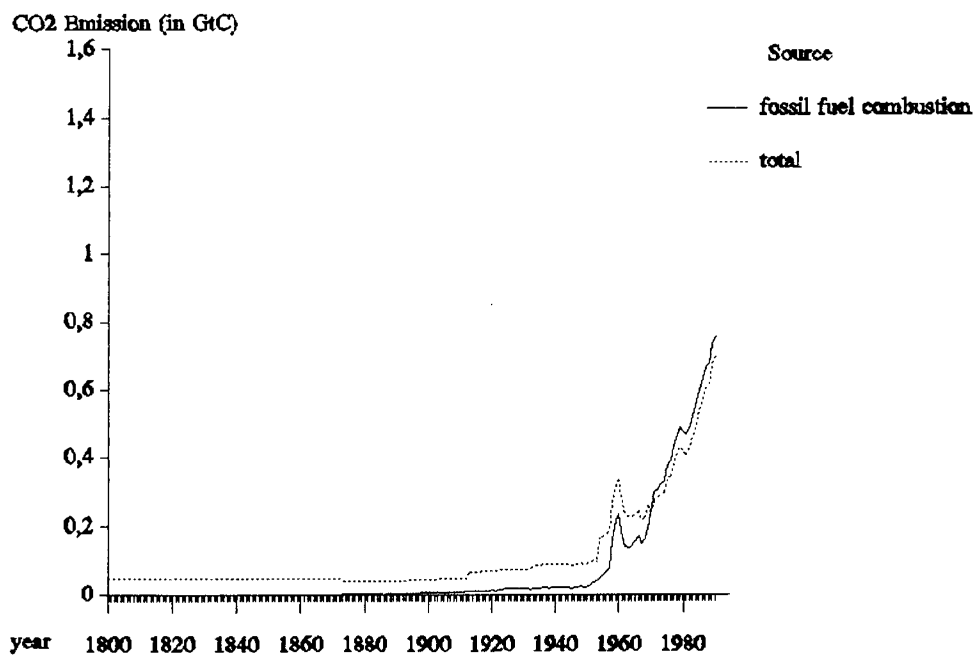

Figure A.2.10: Central Planned Asia.

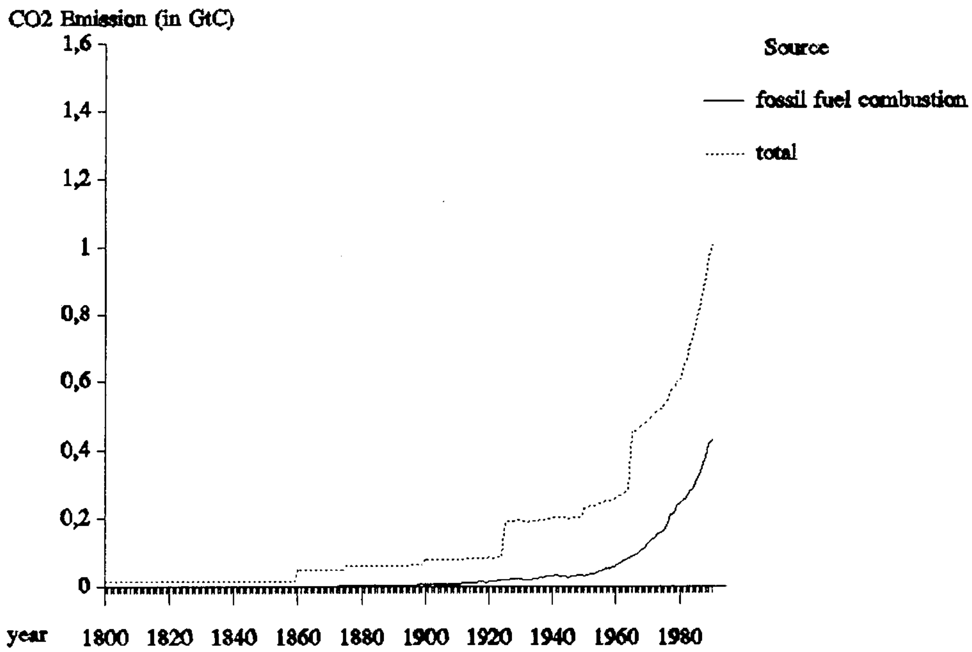

Figure A.2.11: South/Southeast Asia.

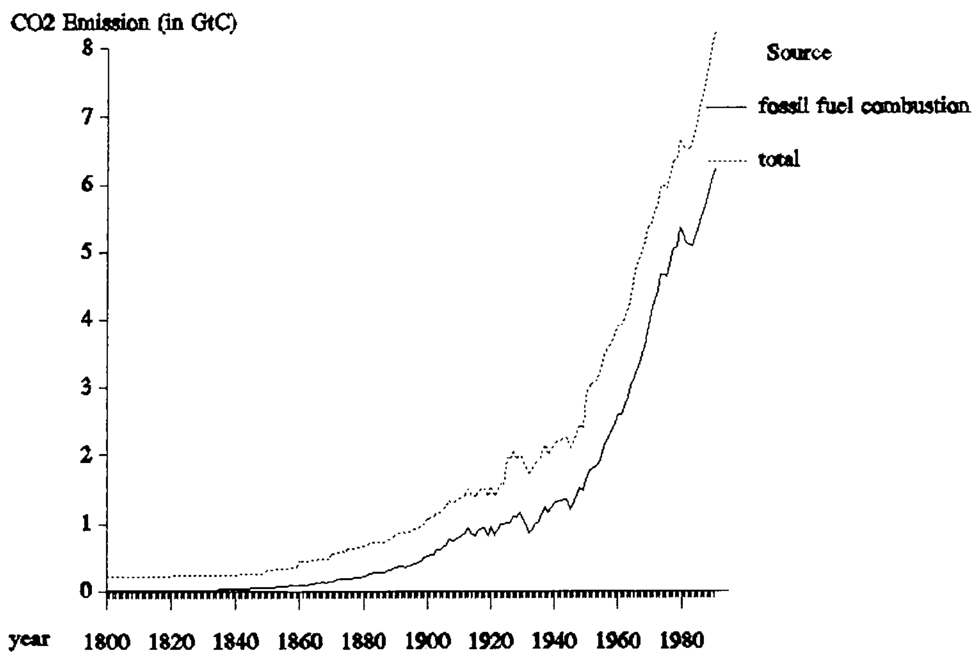

Figure A.2.12: World.

Appendix 3 Land Use Areas

Below are the areas given of ecosystems in each region in the world for different years, estimated with Houghton's data.

1900

(in 10^6 ha)	Europe	Pacific develop-oped	USSR	North America	Latin America	Trop. Africa	North Africa and Middle East	China	South Asia	South east Asia
Trop. moist forest	0	164.6	0	0	487.1	420.2	15.6	8.1	10.9	211.8
Trop. seasonal forest	0	0	0	0	175	479.6	0	0	122.6	37.5
Temp. evergreen forest	74.2	32	108	217.4	26	0	14.0	31.0	0	0
Temp. deciduous forest	55.9	49	106.4	120.6	112	0	0	45.8	0	0
Boreal forest	25.9	0	744.5	392.3	0	0	0	0	0	0
Trop. wood/shrubland	0	17.8	0	0	285	440.9	0	0	167.7	0
Temp. wood/shrubland	45	0	109.5	223.9	347	0	0	0	0	0
Trop. grassland	0	491.6	0	0	74	447.5	81.6	0	180.2	115.8
Temp. grassland	39.6	0	132.4	500.2	484.3	0	0	714.0	0	0
Tundra & alpine meadow	27	0	336	343	0	0	0	0	0	0
Desert scrub	0	118	504	0	0	406	979	145	0	0
Cultivated land	144.3	13.9	145.2	132.7	32.6	72.8	36.7	88.0	88.6	14.9
Pasture land	75	24	53	4	37	187	54	83	7	2

1980

(in 10^6 ha)	Europe	Pacific develop-oped	USSR	North America	Latin America	Trop. Africa	North Africa and Middle East	China	South Asia	South east Asia
Trop. moist forest	0	158.0	0	0	417.1	363.0	5.5	3.7	7.2	199.8
Trop. seasonal forest	0	0	0	0	175	472.1	0	0	83.8	35.4
Temp. evergreen forest	76.2	32	108	214.4	14.5	0	8.1	29.5	0	0
Temp. deciduous forest	62.9	49	90.5	117.5	106.3	0	0	46.2	0	0
Boreal forest	27.9	0	740.3	390.7	0	0	0	0	0	0
Trop. wood/shrubland	0	7.1	0	0	285	392.9	0	0	94.9	0
Temp. wood/shrubland	45	0	90.2	219.4	347	0	0	0	0	0
Trop. grassland	0	465.7	0	0	62.5	410.2	46.5	0	174.1	89.5
Temp. grassland	32.4	0	85.8	443.1	458.1	0	0	674.5	0	0
Tundra & alpine meadow	27	0	336	343	0	0	0	0	0	0
Desert scrub	0	118	504	0	0	406	959.4	145	0	0
Cultivated land	140.8	57.1	231.2	202.0	142.1	222.8	107.4	133.2	210.0	55.3
Pasture land	75	24	53	4	52.4	187	54	83	7	2

1990

(in 10^6 ha)	Europe	Pacific develop-oped	USSR	North America	Latin America	Trop. Africa	North Africa and Middle East	China	South Asia	South east Asia
Trop. moist forest	0	157.7	0	0	389.1	343.4	4.0	3.0	5.9	195.7
Trop. seasonal forest	0	0	0	0	175	470.1	0	0	69.1	34.8
Temp. evergreen forest	78.2	32	108	214.4	9.5	0	8.1	53.5	0	0
Temp. deciduous forest	65.7	49	91.2	117.5	103.9	0	0	46.2	0	0
Boreal forest	29.9	0	740.3	390.7	0	0	0	0	0	0
Trop. wood/shrubland	0	6.6	0	0	285.0	383.4	0	0	75.9	0
Temp. wood/shrubland	45	0	89.9	219.4	347	0	0	0	0	0
Trop. grassland	0	464.5	0	0	58.6	405.4	39.2	0	172.5	84.0
Temp. grassland	33.6	0	85.4	443.1	458.1	0	0	644.6	0	0
Tundra & alpine meadow	27	0	336	343	0	0	0	0	0	0
Desert scrub	0	118	504	0	0	406	953.5	145	0	0
Cultivated land	132.8	59.1	231.2	202.0	165.6	258.7	122.1	139.7	245.9	64.9
Pasture land	75	24	53	4	68.2	187	54	83	7	2

Appendix 4 Comparison of Carbon Fluxes due to Deforestation

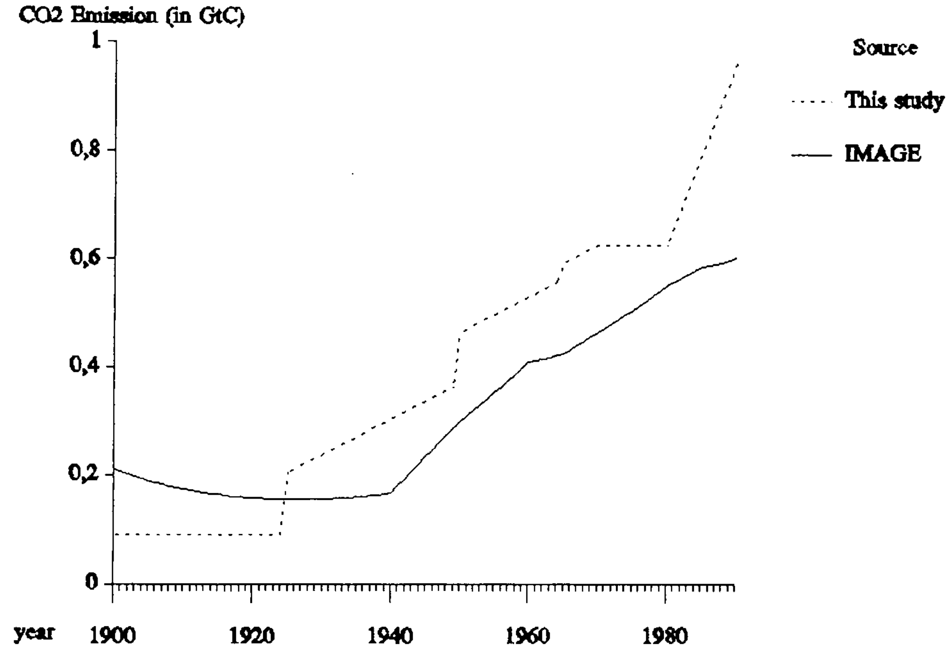

Figure A.4.1: Latin America.

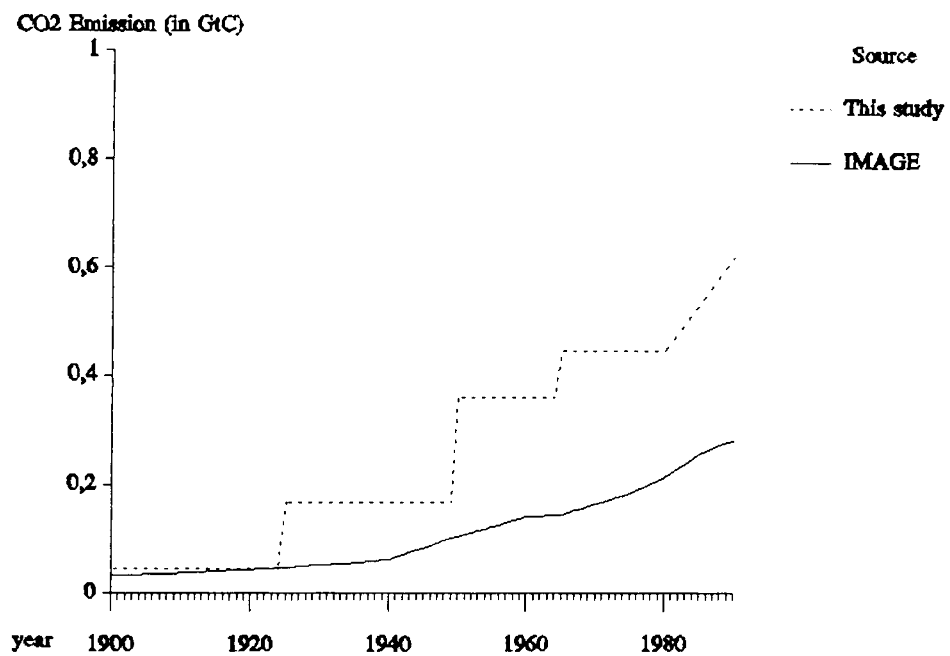

Figure A.4.2: Tropical Africa.

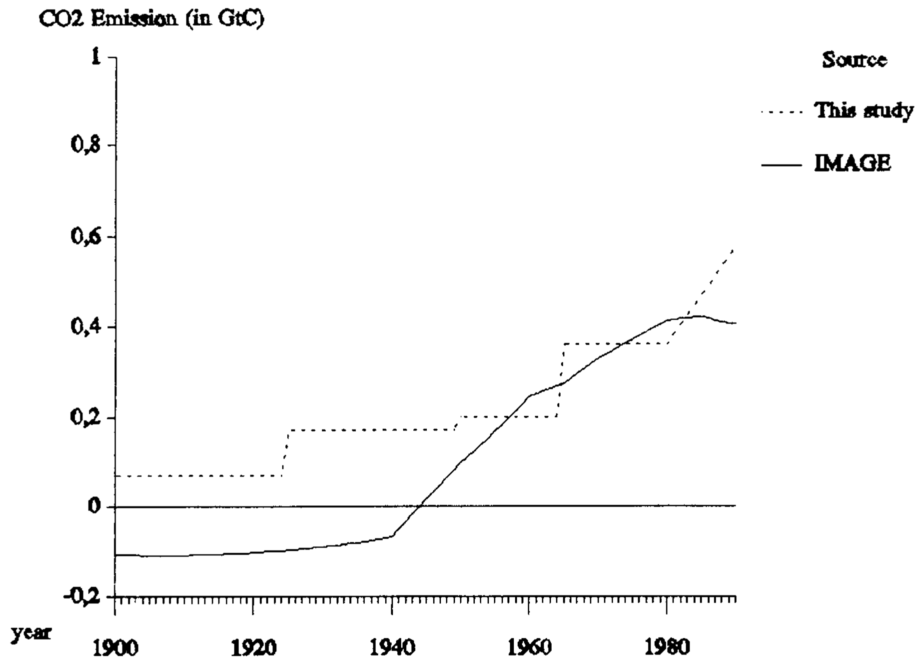

Figure A.4.3: South East Asia.

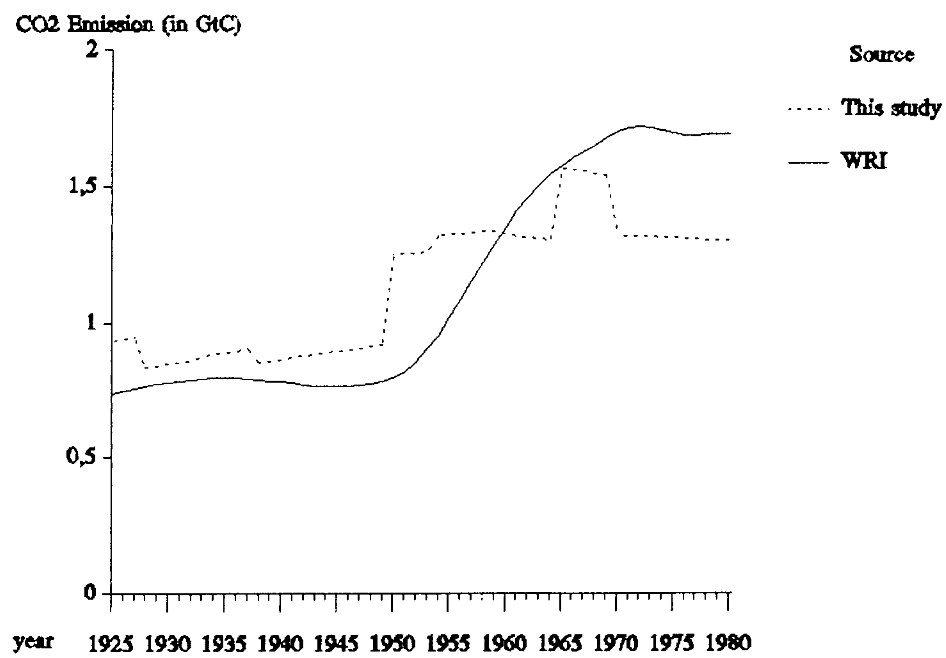

Figure A.4.4: World.

Appendix 5 Population

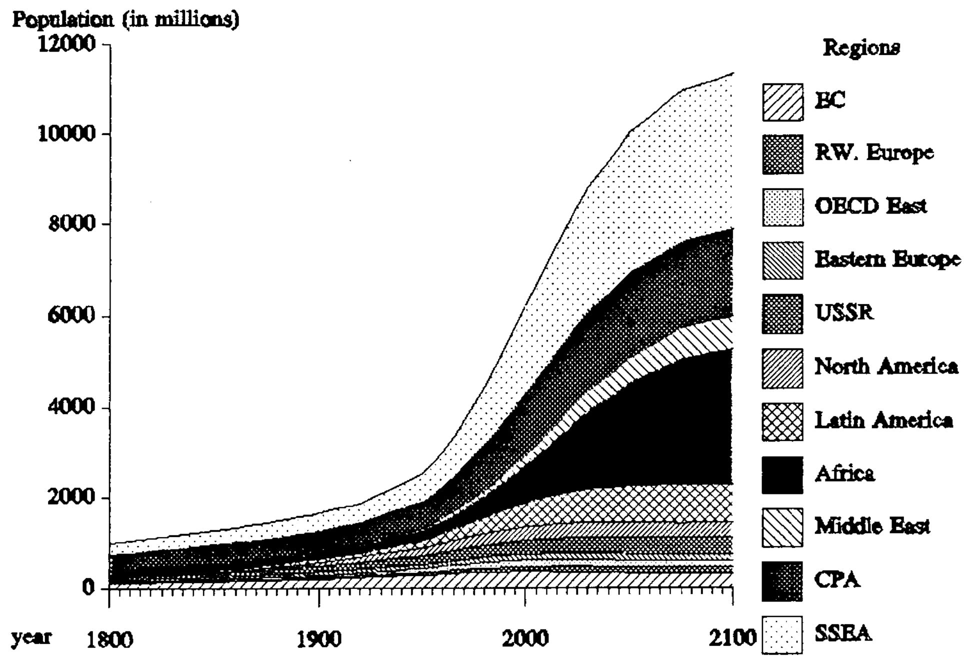

Figure A.5.1: Regional population.

Appendix 6 Relation GNP and Carbon Emissions

Emissions and GNPs of individual countries in 1989 are used to estimate a relation between GNP and carbon emissions due to fossil fuel combustion. A global relation was not significant and therefore different subregions are used. This leads to the following relation.

$$GNP = \alpha_r * EM \tag{A.6.1}$$

with
GNP = Gross National Production (in bil \$)
EM = Carbon emissions by fossil fuel combustion (in mil tC)

Results are given as a 95% confidence interval in Table A.6.1.

Table A.6.1 Confidence intervals

Regions	interval	R^2	n
OECD	$4.18 < \alpha < 4.46$	0.87	24
Latin America	$3.05 < \alpha < 3.41$	0.67	26
South/Southeast Asia	$1.78 < \alpha < 1.93$	0.91	16
Middle East	$1.71 < \alpha < 1.96$	0.79	12
Africa	$1.78 < \alpha < 1.87$	0.71	45
USSR, Eastern Europe and CPA	$0.577 < \alpha < 0.593$	0.99	12

The relation is dependent of characteristics of the economies. Economies in (formally) Central Planned countries have large amounts of carbon emissions relative to their GNP, in contrary to OECD countries. Further analysis gives a higher R^2 for 3 regions with a relation where GNP is dependent of the square root from carbon emissions ($GNP = \beta \sqrt{EM}$) (Table A.6.2). In this relation lead higher emissions with an diminishing rate to higher GNP values.

Table A.6.2 Square root relation

Regions	ß	R^2
South/Southeast Asia	61.5	0.92
Middle East	33.3	0.85
Africa	28.4	0.85

To use above results for this study the α_r are determined for every region in 1990. GNP values for 1990 are estimated to extrapolate the 1989 values. The results (dividing emissions by GNP values) are given in Table A.6.3 These α values could differ sometimes from Table A.6.1 because 1990 data are used and because α in Table A.6.1 are estimated using clustered regions.

Table A.6.3 α_r used in this study

	EC	RWEur	OECDE	EEur	USSR	NAm	LatAm	Afr	MidE	CPA	SSEA
α_r	6.7	8.2	9.4	0.75	0.5	4.0	3.2	2.3	2.1	0.6	2.1