Global environmental change : an integrated modelling approach

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Global Environmental Change

an integrated modelling approach

Michel den Elzen

Global Environmental Change

an integrated modelling approach

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Preface

This thesis examines an integrated modelling approach to two global environmental problems, namely: climate change and stratospheric ozone depletion. Recognition of the fact that both problems are major issues has been increasing among scientists and policy-makers over the last few years. The complexity of such problems, as well as their interrelations, has necessitated the development of a methodology which enables the assessment of various global climate and ozone strategies. This thesis discusses an example of such an integrated assessment tool, an experimental version of IMAGE: an Integrated Model to Assess the Greenhouse Effect. This modelling framework consists of the main modules (submodels) of IMAGE (version 1.6), and the UV-B chain model, which will here be referred to as IMAGE (experimental version 1.6). This dynamic model is designed to incorporate the 'state-of-the-art' scientific knowledge and expertise (including the present-day uncertainties) of the climate change and ozone depletion problem, in a single framework.

The foundation of this integrated modelling framework is the first version of the IMAGE model, which is extensively described in the book *IMAGE: an Integrated Model to Assess the Greenhouse Effect* by Jan Rotmans (1990). This book can be seen as a precursor, as well as an ideal companion to, this thesis.

After a general introduction (Part I), and a description of the modelling framework (Part II), several application studies using the model are presented, which illustrate two central themes of this study: (i) an analysis of (some of) the uncertainties in the field of climate change and (to a lesser extent) ozone depletion (Part III), and (ii) a risk assessment for global climate and ozone policies using a target-oriented approach (Part IV). Furthermore, Part IV introduces preventive ozone and climate policies which reduce environmental risks to tolerable levels. Finally, Part V completes the dissertation with an overview of the main conclusions.

Acknowledgements

As mentioned above, much of the research described in this thesis has been done in cooperation with colleagues at RIVM, who I owe many thanks for their knowledge and efforts. First of all, Jan Rotmans, who as a colleague and later as my professor, introduced me to the field of climate change and global modelling. Without his support, expertise and enthusiasm over the years I would never have finished this thesis. I am also grateful to Koos Vrieze, who stimulated the work through inspiring discussions. A number of colleagues at RIVM, who are also working in the field of climate change and ozone depletion, have given generously of their knowledge and assistance. In particular, I would mention Eric Kreileman, Maarten Krol, Harry Slaper, Rob Swart, Bert de Vries and Hans van der Woerd. I would also like to thank my trainees for their research, especially Marco Janssen for his enthusiasm and creative ideas in developing the emission debt concept, and Anne-Marie Harbers for her effort in conducting an uncertainty analysis of the entire model. I am also grateful to Peter Janssen and Peter Heuberger of the Centre of Mathematical Methods for their helpful comments.

Special thanks are due to Martin Middelburg, who was responsible for the graphics and layout of this publication, and stimulated me through his 'endless' requests for more figures and text. Finally, I would like to thank Alan Miller for his great effort in correcting and improving the English text.

Writing a thesis in your spare time for more than a year is not only a taxing venture for the author, but also for everyone around him. I therefore thank my parents, Monique and my friends, for their patience and support throughout.

Part I General introduction

1 Introduction

Global environmental change: an introduction

Human activities have significantly affected the structure and the functioning of the Earth system. Our use of land, water, minerals and other natural resources has increased more than ten-fold during the past 200 years, and future increases in population and development will only intensify this pressure. Large-scale chemical transformations and natural transfers of energy and materials around the world are involved (IGBP, 1992). During the last few decades we have seen increasing acceptance of the insight that the increase in magnitude and complexity of such large-scale problems causes serious harm, varying from a disruption of local ecosystems up till global disturbance of the biosphere as a whole.

In this study the totality of changes on planet Earth, including all human interventions and alterations, is considered as global change. The concept of global change is broader than the concept of environmental change. The latter only refers to the human-induced biophysical changes to the dynamics of the Earth system, while global change refers to changes of both the biophysical and the human system (Rotmans, 1993).

In practice, the concept of global environmental change is an umbrella term which covers a range of individual, albeit interdependent global environmental problems, which can be subdivided into three groups (RMNO, 1990; Döös, 1991; UNEP, 1992; Elzen and Rotmans, 1993b):

1. climate change, stratospheric ozone depletion, atmospheric deposition (including acidification), eutrophication, tropospheric ozone increase and photochemical smog;

2. deforestation, erosion, land degradation and desertification;
3. dispersion of chemicals: heavy metals and persistent and toxic micropollutants.

All these global environmental problems share the following characteristics: they are primarily caused by human activities, the effects of these problems are widespread, and affect the present and future economy, the rate of change is so rapid that it can be detected within a human lifetime, and finally the change is potentially irreversible (O'Riordan and Rayner, 1991).

Widespread recognition of global change followed the publication of the first Report to the Club of Rome by Meadows *et al.* (1972), which was met with a great deal of criticisms. In the mid-seventies, Rowland and Molina (1974) launched their theory on the depletion of the stratospheric ozone layer by chlorofluorocarbons, and thus achieved a breakthrough which led to awareness that human activities have consequences on a global scale. Within a short time, the issue became the prime illustration of the necessity to study the phenomenon of global environmental change, and the associated research into atmospheric processes stimulated the study of other global environmental problems. Next on the scene was the problem of acidification, although strictly speaking not a global problem but rather a problem for pertaining to specific continents, and this was succeeded by interest in climate change. Later, other global environmental problems became the subject of research, such as deforestation, land degradation, erosion, desertification, and large-scale chemical pollution.

The scope, objectives and methodology of this study

This thesis focuses on two major global environmental problems, namely: climate change and stratospheric ozone depletion (and their mutual interactions). Both of which are presently of major public and political concern due to their potential environmental threat to all life on Earth in near future. Interactions with other global environmental problems, except the linkages with land use changes (including deforestation), are not considered here.

The main objective of this study is the development of an integrated, multi- and interdisciplinary simulation model, which is designed to sketch 'state-of-the-art' knowledge and expertise in a comprehensive overview. Estimates of the scientific uncertainties about climate change and stratospheric ozone depletion (IPCC, 1990; 1992, and WMO, 1992), will be included by coupling the causes (social and economic processes), mechanisms (chemical and biophysical processes) and (some of the) effects on society, ecosystems and humans.

Further objectives of this study related to the development of such an integrated assessment framework are:

1. to identify and analyse some of the present main uncertainties and lacunae,
2. to calculate, assess and evaluate the implications of various climate and ozone strategies^[1] in the light of future risks, and to develop preventive or ameliorative policies, which reduce risks to tolerable levels.

As a starting point for the development of such an integrated modelling framework (main objective), the climate assessment model IMAGE: an Integrated Model to Assess the Greenhouse Effect (version 1.0) (Rotmans, 1990) was used. This policy-oriented model was enhanced in several

aspects, and updated in that it incorporates data of IPCC (1990;1992), such as:

- the IPCC-1990 and IPCC-1992 emission scenarios;
- the latest data of the sources, sinks and atmospheric lifetimes of greenhouse gases;
- an improved atmospheric chemistry model (including additional processes and gases);
- various biogeochemical feedback mechanisms.

These enhancements led to IMAGE (version 1.6).

Subsequently, the UV-B chain model (coupled halocarbon/UV-B impact model) was developed as a computational tool able to describe the entire cause-effect chain implied by the ozone depletion issue. This ranged from the production and consumer use of CFCs and other halocarbons (causes), i.e. the ozone depleting mechanisms, to (some of the) effects on human health (skin cancer incidence) of stratospheric ozone depletion for certain specific regions. This model was integrated, together with the quantitatively understood interactions between climate change and stratospheric ozone depletion, into IMAGE (version 1.6), and resulted integrated framework, here referred to as IMAGE (experimental version 1.6), is used to pursue the other objectives of this study.

As its first objective, this thesis surveys the main contemporary uncertainties and lacunae in the field of climate change and stratospheric ozone depletion. Those uncertainties which can be quantitatively estimated were incorporated in the modelling framework IMAGE (experimental version 1.6), and their influence on the model outcomes (climate and ozone projections) is examined using the techniques of sensitivity and uncertainty analysis, and scenario analysis.

In the pursuit of its second objective, a risk assessment approach was applied which recognises the limits of scientific certainties in the field of these global environmental problems, and uncertainties about its possible impacts. This methodology involves assessing projected risks of various climate and ozone scenarios by coupling these sce-

[1] A climate strategy is an 'abbreviation' for a strategy which is designed to stabilize or influence climate change, whereas an ozone strategy is an 'abbreviation' for a strategy which is designed to counter stratospheric ozone depletion.

narios with long-term targets (specific levels of a chosen indicator). In the present context, a policy is associated with high risks if the chosen indicator exceeds the target value over a longer term, whereas in the case of a policy which meets the target, the anticipated risks tend to acceptable levels. Here, the climate change indicators considered here not only include the rates and magnitudes of temperature increase and sea level rise, but also the socio-economic effects, especially the flooding frequency of the Dutch coastal defence system. In the case of ozone depletion, the indicators are: atmospheric chlorine concentration and mortality risks due to skin cancer caused by stratospheric ozone depletion. In addition, the methodology can be applied to the development of preventive strategies which meet the targets, and thus limit the impacts and risks inherent in the global environmental problem to a tolerable minimum (risk-minimization approach).

Scientific background

Through the years of the development of the IMAGE model (version 1.6), numerous articles and technical reports on the different aspects of the model and its use have been published. An overview of the papers (co-) authored by the present author, which formed the major basis for the climate change topics described in this thesis, is given below. Issues related to ozone depletion, including a description of the UV-B chain model, as well as model studies, have not yet been published in the international literature, although they have appeared in RIVM reports.

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Schematic plan of the thesis

This thesis has been devised in five parts.

In Part I 'General introduction' (Chapters 1-2), the present state of knowledge of both global environmental problems is briefly surveyed.

Part II 'Methodology' (Chapter 3) offers a brief description of the integrated modelling framework IMAGE (experimental version

Part I	General introduction
	1. Introduction
	2. Problem setting
Part II	Methodology
	3. Modelling framework
Part III	Uncertainty analysis
	4. Introduction
	5. Uncertainties: social factors
	6. Uncertainties: sources/sinks CO ₂
	7. Uncertainties: sources/sinks CH ₄
	8. Uncertainties: model parameters
Part IV	Risk assessment: a target-oriented approach
	9. Introduction
	10. Ozone risks: ozone targets
	11. Climate risks: climate targets
	12. Climate risks: impact targets
	13. Ozone risks: public health targets
	14. Policy analysis: allocating emission rights
Part V	Conclusions
	15. Conclusions

Schematic structure of the thesis

1.6). Some specific parts of the model are described in more detail in other Chapters, e.g. the carbon cycle model (Chapter 6), the atmospheric chemistry model (Chapter 7), the halocarbon model (Chapter 10), and the UV-B impact model (the UV-B chain model) (Chapter 13).

In Part III 'Uncertainty analysis' (Chapters 4-9), an uncertainty analysis of climate change, and to a lesser extent, stratospheric ozone depletion is presented. Chapter 4 discusses the main uncertainties associated with climate change and stratospheric ozone depletion, by dividing them into two categories: 'scientific uncertainties' and 'social and economic uncertainties'. It also presents the sensitivity and uncertainty analysis techniques, which are employed in this study. Chapter 5 briefly reviews the social and economic uncertainties implied by future greenhouse gas emissions (emissions scenarios). Chapters 6 and 7 describe a model and sensitivity analysis pertaining to the scientific uncertainties and/or lacunae in the sources and sinks of methane and carbon dioxide, and their biogeochemical feedback processes. Chapter 8 presents an uncertainty and

sensitivity analysis of the carbon cycle model, the halocarbon model, and the IMAGE model (experimental version 1.6) as a whole.

Part IV (Chapters 9-14), entitled 'Risk assessment: a target-oriented approach' firstly presents the risk assessment methodology (based on the principle of connecting long-term climate and ozone strategy with the long-term environmental targets) as applied to the problems of climate change and stratospheric ozone depletion more specifically (Chapter 9). In Chapter 10, this methodology is used as a means with which to assess current ozone policy, as defined in the Copenhagen Amendments to the Montreal Protocol, and a wide range of halocarbon policies, based on the indicator, namely: atmospheric chlorine concentration, and the ozone targets as defined by the World Meteorological Organization (WMO, 1992). Chapter 11 presents and evaluates the simulated globally-averaged temperature and sea level rise (indicators) for the IPCC-1990 scenarios, as well as the IPCC-1992 scenarios with respect to the climate targets, as formulated by the Advisory Group on Greenhouse

Gases (AGGG). This Chapter concludes with the presentation of a preventative climate policy, here referred to as: Low Risk scenario, which would meet the climate targets. Chapter 12 discusses the impact of sea level rise on the frequency of the Dutch coastal defence system (indicator) for the IPCC-1990 scenarios being subjected to flooding, and thereby evaluates the changes in flooding frequency with respect to the present safety norm (target), the so-called 'Delta-norm' (Delta Commission, 1960) from a risk perspective. Chapter 13 presents projections of mortality rates due to stratospheric ozone depletion based on model simulations employing the UV-B chain model for a number of halocarbon policies (including the Copenhagen Amendments), and evaluates these results with respect to the public health risk targets, which are based on health risk

targets for ionized radiation, as formulated by VROM (1992). Chapter 14 presents for the climate scenarios, namely: IPCC-1990 scenarios, as well as the Low-Risk scenario, an approach for allocating future emissions of CO₂ among regions, based on an equity rule, by which all past and future inhabitants on the Earth are permitted to emit an equal CO₂ quatum per year. The resulting initial allocation of emissions may be used as a start for a concept of tradeable emission rights.

Part V 'Conclusions' (Chapter 15) gives a summary and presents the dissertation's conclusions, and moreover evaluates the IPCC-1990 scenarios and the Low-Risk scenario in a broad perspective of all climate and ozone targets.

2 Climate change and stratospheric ozone depletion

2.1 Introduction

Since the beginning of the industrial time societies have been creating hostages to fortune in their impact on the Earth and its atmosphere. Emissions resulting from human activities are increasing the worldwide atmospheric concentrations of carbon dioxide, methane, nitrous oxide, chlorofluorocarbons (CFCs), and many other trace gases (the so-called 'greenhouse gases'). The primary activities responsible for this increase are: the world-wide use of fossil fuels to supply a growing world population with energy, the land use changes, agricultural activities, and the use of CFCs. The increasing atmospheric concentrations of these gases have caused two global environmental problems namely: stratospheric ozone depletion and climate change.

The basic theory of the ozone depletion problem, i.e. that the emissions of CFCs and other halocarbons (all chlorinated and brominated chemicals) lead to the destruction of ozone, was developed in the mid-seventies. The first serious indication that this theory was valid occurred in the mid-eighties by the discovery of the springtime Antarctic ozone hole, which was already initiated in the late 1970s. At that time, scientific evidence that CFCs were responsible for this ozone hole was mounting, although there was still no satisfactory scientific proof. In 1987, despite the gaps in knowledge the first international policy, the Montreal Protocol, which regulates the consumption of the five main CFCs to 50% of their 1986 levels by the end of this century was signed. Recent analyses of satellite measurements revealed massive ozone depletion above the Antarctic during recent years, and also significant reductions during the 1980s at the middle and high latitudes. These developments moved policy-makers to

bolster the Montreal Protocol in the London Amendments of 1990, which prescribe a phasing-out of a large group of halocarbons (including the CFCs regulated by the Montreal Protocol) by the year 2000. In 1992, the scope of this phasing-out scheme was further advanced to 1996 by the Copenhagen Amendments. Currently strong scientific evidence is available to suggest that the chlorinated and brominated chemicals are primarily accountable for the Antarctic ozone hole, and that the observed middle- and high-latitude ozone losses are also largely due to these chemicals. *Figure 2.1* illustrates the major steps in the complex process from the identification of the stratospheric ozone problem up to the adoption and implementation of international response strategies which provide sufficient environmental protection.

In addition to their role in ozone depletion, CFCs and other halocarbons are among the radiatively-active trace gases (or greenhouse gases), which contribute to climate change. The climate change problem, or global warming as it is popularly known, is based on the theory that the increasing atmospheric concentrations of greenhouse gases due to the emissions resulting from human activities enhance the greenhouse effect, and may induce an increase in the Earth's surface temperature, and thus change the climate of the planet. As early as 1896, Arrhenius argued that the carbon dioxide (CO₂)/greenhouse effect issue could be a possible environmental threat. However, it was not until the mid-1970s that any attention was paid to this environmental issue, and it is less than ten years since the fact that other trace gases also play a role in this problem was recognized. At present, there is virtually no debate among scientists about whether increasing atmospheric concentra-

Figure 2.1: Schematic illustration of the complex process of achieving sufficiently powerful and binding international response strategies for stratospheric ozone depletion and climate change (Döös, 1991).

tions of greenhouse gases raise the Earth's surface temperature, and the only controversy concerns the magnitude and the rate of such a rise. The global mean surface temperature has increased by between 0.3 and 0.6°C over the last hundred years, and the five, globally-averaged warmest years occurred in the 1980s. Since the temperature increase is of the same magnitude as the 'natural' climate variability, detection of the problem remains problematic. An unequivocal detection is also not to be expected in the coming decade(s) (IPCC, 1990). Despite this lack of detection and the significant uncertainties inherent in the problem, the issue of climate change entered the policy debate in the late 1980s. In 1988, at the Conference on the Changing Atmosphere in Toronto (WMO, 1988), scientists and policy-makers formulated a recommendation for a global reduction in CO₂ emissions of 50% around 2025, which would be sufficient to stabilize atmospheric concentrations. In 1992, at the United Nations Conference on Environment and Development (UNCED) at Rio de Janeiro, a Framework on Climate Change Convention was signed, calling for the control of greenhouse gases. *Figure 2.1* also summarizes the present state of play in the climate change problem in terms of the major milestones in its history.

In this Chapter, the scientific understanding of both of the global environmental problems, including their causes, mechanisms, effects, and interactions, are reviewed. A detailed description of the history of both problems in the perspective of the five stages is offered in sections 2.2 and 2.3. The sources and sinks of the trace gases associated with both phenomena are described in section 2.4.

2.2 Stratospheric ozone depletion

2.2.1 The problem

Worldwide concern about the issue of stratospheric ozone depletion soon developed after the American scientists, Molina and Rowland, warned that the use of CFCs might damage the ozone layer (Molina and

Rowland, 1974). The measurements of the Antarctic ozone hole, and the middle- and high-latitude ozone losses evince the seriousness of this environmental problem. Since the ozone layer shields the Earth's surface from biologically harmful ultraviolet (UV) radiation, future ozone depletion might lead to increases in UV-B radiation, which might cause a multitude of negative effects; augmentations in the incidence of skin cancer and other diseases, reduction of crop yields (directly affecting the world food supply) and damages to materials. Another impact is directly linked with the climate change issue: the depletions of ozone in the lower stratosphere during the last decade have caused a decrease in radiative forcing which could offset a fraction of the global warming attributed to the increases in the abundance of all greenhouse gases over that period. An indirect impact on global warming should also be mentioned: rises in UV-B radiation can impair the primary production of phytoplankton, and will thus limit the oceans' capacity for taking up carbon dioxide. A reduction in the oceans' capacity will therefore increase the atmospheric carbon dioxide concentration, and therefore contribute to the enhanced greenhouse effect.

What chemical mechanisms are associated with ozone depletion?

Solar radiation, particularly in the high-energy UV range is the driving force behind ozone chemistry over all latitudes. The first theory of the formation and depletion of ozone molecules was developed by Chapman (1930).

Chapman's theory:

Stratospheric ozone formation occurs in the process of photodissociation by which an oxygen molecule (O₂) is split into two individual atoms oxygen (O) when exposed to shortwave UV radiation:

where $h\nu$ is an absorbed photon in the UV range.

Each of these oxygen atoms can react with an oxygen molecule and thereby form a tri-atomic ozone molecule (O_3):

where M is the collisional molecule required for the reaction, since it absorbs the energy released.

The net reaction for ozone formation is now described as:

As counterparts to the natural ozone formation processes, there are also a number of ozone decomposition processes:

1. Ozone molecules can be broken down into their individual components by exposure to radiation of longer wavelengths (photo-dissociation):

2. A second ozone destruction mechanism is the reaction between an O atom and an O_3 molecule.

The net reaction for ozone decomposition is thus:

The catalytic cycles:

If the global ozone profile was to be calculated on the basis of the reactions according to the Chapman theory, the density of the ozone layer would be 50% greater than that which is actually observed in the stratosphere. This fact inspires the conclusion that there must be other ozone depleting reactions involved.

In the fifties it was found that these reactions are catalytic processes, i.e. processes in which the catalyst released by photodecom-

position of the trace gas involved assist the destruction of stratospheric ozone, but at the end of the reaction the catalysts remain in their initial form. Such a catalyst can destroy many thousands of O_3 molecules via such catalytic cycle reactions. So far only OH (involved trace gas methane) was detected as a catalyst, in the beginning seventies NO (from N_2O) followed, and in mid-seventies chlorine (from CFCs) came on the scene (Molina and Rowland, 1974).

The catalytic reactions involved for a general catalyst X and its radical XO are as follows:

In the first step the catalyst X reacts with the ozone molecule, to form an O_2 molecule and an intermediate product XO . In the second step, XO reacts with an oxygen atom to reconstitute the catalyst and an oxygen molecule. The catalyst X (e.g. H , OH , NO , Cl and Br) and its radical XO (HO , HO_2 , NO_2 , ClO and BrO) undergo no chemical changes. These catalysts and radicals are reactive, unstable substances. Their concentrations have been increasing in recent years as a result of human activities. This is specially true for atmospheric chlorine concentration, which has increased rapidly, by a factor of approximately 6 to 7 against the natural value. The latter is mainly a result of the emissions of CFCs.

The main stratospheric reactions for the CFCs are subsequently: first, the formation of ClO_x radicals by photodecomposition of these compounds at wavelengths found at the stratospheric window, and/or by the reaction of OH radicals or an excited oxygen atom O^* , which is formed by photodecomposition of O_3 at a wavelength smaller than 310 nm. And second, the catalytic reactions, as described in Equation (2.7), leading to stratospheric ozone depletion.

The emissions of CFCs and other chlorinated chemicals are, although a major cause of the observed ozone losses over the last decades, not the only factors which affect the

stratospheric ozone concentration. Three major causes of changes in stratospheric ozone can be considered:

1. natural causes: the three cyclical phenomena (the seasons, the quasi-biennial oscillations (QBO), and the eleven-year solar cycle)
2. irregular phenomena, such as volcanic eruptions, the El Nino event and polar stratospheric clouds (PSCs).
3. man-made causes: the emissions of halocarbons and sulphate aerosols, and other human causes with a minor negative impact on stratospheric ozone: supersonic aircraft, shuttles, and rockets.

Their influence on stratospheric ozone will be described in section 2.2.2.

Ozone depleting substances:

Fully halogenated halocarbons (CFCs, CCl_4 , and halons) are robust compounds which survive tropospheric 'clean up' processes and, after leakage into the lower atmosphere, diffuse up to the higher atmospheric levels, where they photodecomposed. The main fully halogenated halocarbons are: CFCs (CFC-11, CFCl_3 ; CFC-12, CCl_2F_2 ; CFC-113, $\text{C}_2\text{Cl}_3\text{F}_3$; CFC-114, $\text{C}_2\text{Cl}_2\text{F}_4$; CFC-115, C_2ClF_5), carbon tetrachloride (CCl_4) and halons (halon-1211; CBrClF_2 ; halon-1301; CBrF_3). These compounds are currently being used as aerosol propellants (CFC-11, CFC-12, CFC-113, CFC-114), foams (CFC-11, CFC-12, CFC-113, CFC-114), refrigerants (CFC-11, CFC-12, CFC-114, CFC-115), solvents (CFC-113, CCl_4), and fire retardants (halons).

Non-fully halogenated halocarbons (methylchloroform (CH_3CCl_3), HCFCs and HFCs) are hydrogen based compounds which are to some extent removed in the troposphere by the reaction with OH, many of which thus have no effect on stratospheric ozone because they do not reach the stratosphere. For this reason they, in particular HCFCs and HFCs, are currently proposed as substitutes for the fully halogenated halocarbons (some already in use).

2.2.2 Historical development

CFCs were first produced in laboratories at the end of the last century. The industrial-scale production of the most important CFCs, i.e. CFC-11 and CFC-12, started in the beginning of the 1930s, and rose constantly until 1974. As mentioned above, the first warnings regarding the consequences of damage to the ozone layer through the use of CFCs were issued in 1974 (Molina and Rowland, 1974). As a result of the public discussions and political debates, policy-makers in a number of Western industrialized nations took measures to reduce the use of the compounds. The CFC production for aerosols, and hence overall, decreased in the second half of the seventies and continued to fall until the early eighties, when it once more slowly increased again in the subsequent years.

The predictions put forward by Molina and Rowland stating that the ozone layer might be damaged by the use of CFCs remained theoretical until 1985, when the world was shocked by the discovery of the springtime Antarctic ozone hole, which had already started to develop in the late 1970s (Farman *et al.*, 1985).

In 1987, global concern about the damaging effects of CFCs and other halocarbons on stratospheric ozone, led to 24 nations signing an international agreement controlling the production and consumption of a number of fully halogenated CFCs and halons: the Montreal Protocol (UNEP, 1987). According to this protocol, the production and consumption of the ozone depleting substances CFC-11, CFC-12, CFC-113, CFC-114 and CFC-115 should initially be frozen in the developed countries at their 1986 levels by the year 1990, reduced to 80% of their 1986 levels by the year 1993, and reduced to 50% of their 1986 levels by the year 1998. The production of the halons (halon-1211, halon-1301, halon-2402) was to be frozen at the 1986-levels by 1992.

After the establishment of the Montreal Protocol, new scientific evidence indicated that the rise in stratospheric chlorine and bromine levels caused by halocarbon emissions is primarily responsible for the observed sub-

stantial decline in stratospheric ozone over Antarctica in 1987 and 1989, and the more modest depletion of 3 to 5% over the period 1969 to 1988 in wintertime above northern midlatitudes (30–60°N), the results of analysis of total column ozone data from ground-based Dobson instruments (WMO, 1990a). These findings prolonged the discussions concerning a possible adjustment of the Montreal Protocol, and, in 1990, led to a strengthening of the Montreal Protocol in the form of the London Amendments (UNEP, 1990), which set out a stricter reduction scheme for the regulated and other fully halogenated CFCs and the halons, namely: a 50% reduction by 1995, an 85% reduction by 1997 and a complete phase-out by the year 2000. The carbon tetrachloride and methylchloroform emissions are to be phased-out by 2000 and 2005, respectively.

Observations taken over the last six years demonstrate that in the Antarctic springtimes of 1987, 1989, 1990, 1991, 1992, the ozone column was reduced by more than 50%, and more than 95% of the ozone concentrations found at altitudes between 15 and 20 km was destroyed (WMO, 1992; 1992a). The spring of 1992 was one of the lowest years in this record. The areal extent of the Antarctic

ozone hole remained essentially constant. In 1992, the area was about 15% larger than in the previous years for about 2 weeks. The total ozone observations are consistent with the observed removal of 90% or more of the ozone in this region by polar stratospheric clouds (PSCs) (WMO, 1992a). At this time it is known that the formation of polar stratospheric clouds (PSCs), composed of water ice and nitric acid trihydrate, is particularly important to the formation of an ozone hole. The main chemical cause of ozone depletion results from catalytic cycles involving chlorine and bromine liberated from chemically inert reservoir molecules by heterogeneous reactions on the PSC surfaces. Since the formation of PSCs occurs less above the Arctic, there is up to now (1993) no Arctic ozone hole observed. Also the formation of PSCs was lower in number above the Antarctica in 1988, which explains why then the ozone hole was smaller. Scientific evidence demonstrates that chlorinated and brominated chemicals are primarily responsible for the decline in Antarctic ozone (WMO, 1992).

As a complement to these observations, Stolarski *et al.* (1991) analysed ozone trends derived from the satellite measurements taken by Nimbus 7 Total Ozone Mapping

Figure 2.2: Percentage ozone depletion trends per decade as a function of latitude and seasons, based on TOMS data collected between November 1978 and March 1991 (WMO, 1992).

Table 2.1: Total ozone trends in percentages per decade with 95% confidence limits (WMO, 1992)

	TOMS: 1979-1991			Ground-based: 26°N-64°N	
	45°S	Equator	45°N	1979-1991	1970-1991
Dec-Mar	-5.2±1.5	+0.3±4.5	-5.6±3.5	-4.7±0.9	-2.7±0.7
May-Aug	-6.2±3.0	+0.1±5.2	-2.9±2.1	-3.3±1.2	-1.3±0.4
Sep-Nov	-4.4±3.2	+0.3±5.0	-1.7±1.9	-1.2±1.6	-1.2±0.6

Spectrometer (TOMS) over the time period from November, 1978 through May, 1990, and found that after correction for known natural influences, the average total ozone between the latitudes 65°S and 65°N was exhibiting a total mean decreasing rate of about $0.26 \pm 0.14\%$ /year (the range represents a 95% confidence interval) over that period (Figure 2.2). No statistically significant ozone trend was found for the tropical belt (between 30°S and 30°N latitudes). A negative ozone trend of 4% or more was found at all latitudes south of 40°S throughout the year. The 50°N annually averaged trend is $-0.5 \pm 0.2\%$ /year, with a seasonal variation over that period of -0.8% /year in February and March and -0.2% /year in July and August. For the first time, there is a statistically significant decrease in spring and summer in both the Northern and Southern Hemispheres at middle and high latitudes, as well as in the southern winter (see Table 2.1). All measurements show that the major ozone decline occurred in the lower stratosphere (about 13-25 km in middle latitudes), at a rate of 10% per decade (Stolarski *et al.*, 1991; WMO, 1992). Furthermore, based on recent laboratory research and re-interpretation of field measurements there is strong evidence that the observed ozone losses at middle and high latitudes are largely due to chlorine, and to a lesser extent to bromine (WMO, 1992).

In 1992, NASA satellite observations produced alarming high figures for active chlorine-monoxide levels over large parts of middle and high latitudes of the Northern Hemisphere, indicating CFCs as the dominant source (NASA, 1992). Sulphate aerosols from the volcanic eruption of the

Pinatubo in the summer of 1991 could have initiated and accelerated heterogeneous processes which can lead to elevated chlorine-monoxide levels. It was expected that the induced ozone depletion could even reach 30-40% under unfavourable weather conditions during the early spring months. Although these alarming figures were at that time preliminary, as an immediate response the EC adopted a policy designed to phase-out the regulated halocarbons earlier, i.e. in 1995.

At the end of 1992, the London Amendments were again reinforced by another international agreement, the Copenhagen Amendments, which limit the production and consumption of the regulated CFCs, CCl_4 , and CH_2Cl_2 to a phase out by 1996, and that of the halons by 1994. As regards to the alternative HCFCs, the level of consumption was to be limited at a maximum level of consumption (calculated in Ozone Depletion Potential or ODP tonnes), equal to the sum of calculated 1989 consumption of HCFCs and 3% of calculated 1989 consumption of CFCs. The phase-out would then proceed in three steps, a 25% reduction in the period 2000-2005, a 50% to 75% reduction for the period 2005-2015, and a total phase-out between 2010 and 2030.

2.2.3 Modelling ozone depletion

Predictions of future ozone losses are examined using global two and three dimensional models of stratospheric chemistry and transport. Three types of 2-D or 3-D models can be considered: models including only gas chemistry (GAS), models including currently known heterogeneous processes associated

with sulphate aerosols (HET), and models incorporating a parametric formulation of the chemistry involving polar stratospheric clouds (PSC) (Prather *et al.*, 1992). GAS models calculate ozone losses over the period 1980-1990 as being much less than that observed at middle latitudes over all seasons in both hemispheres (WMO, 1992). HET models simulate most of the observed trend of column ozone in northern and southern middle latitudes in summer over the same period, but only about half of that in winter. PSC models are still under development, but simulate greater ozone losses at northern middle latitudes in winter.

HET models forecast that the maximum ozone losses will occur around 2000, with the extra losses over the period 1990-2000, as being equal to or slightly less than, those obtaining in 1980-1990. Further future ozone losses over the period 2000-2050 depend on changes in numerous factors: stratospheric chlorine, bromine, NO_y (from N_2O) and methane levels, and stratospheric temperature (through CO_2 and enhanced greenhouse effect). Model outcomes therefore differ greatly (Prather *et al.*, 1992).

In addition these atmospheric models, Prather and Watson (1990) introduced a simple numerical model for calculating the future changes in atmospheric chlorine and bromine concentrations resulting from halocarbon emissions. Chapter 10 describes a halocarbon model, which is in complexity comparable to the model of Prather and Watson (1990).

2.3 Climate change

2.3.1 The problem

There is a growing concern that emissions of carbon dioxide and other radiatively-active trace gases, or greenhouse gases, resulting from human activities might cause an increase in the Earth's surface temperature, and change the climate of the Earth by means of an enhanced greenhouse effect. This global change will not only manifest itself in altered patterns of surface tempera-

ture and precipitation, but might also cause all kinds of impacts, such as droughts (desertification), sea level rise, shifts in the growing zones for vegetation (both natural and agricultural), and changes in the supply of freshwater for human use, etc. These diverse impacts certainly imply great economic, social and political implications. Sea level rise is a particular threat to densely-populated low-lying countries and could damage coastal areas and ecosystems. On the other hand, climate change could also provide benefits to some countries. For example, increased rainfall or longer growing seasons in the present marginal areas for crop production would simply be welcomed by the affected countries.

How does the greenhouse effect work?

The theory of the greenhouse effect is scientifically well established. The Earth and its atmosphere receive short-wave solar radiation from the sun. About 30% of this incoming solar radiation is reflected back into space, mainly by clouds. The rest is absorbed by the atmosphere and the Earth's surface, before it is emitted as long-wave thermal radiation into space (see *Figure 2.3*). Most of this long-wave radiation is absorbed by a number of radiatively-active trace gases (greenhouse gases), like water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and ozone (O_3). These gases share an important physical property in that they absorb radiant energy at infrared wavelengths much more efficiently than at solar wavelengths, and thus trap most of the radiant heat emitted from the Earth's surface before it arrives in space. These gases and particles not only absorb infrared energy, but also give it off. This re-radiated infrared radiation is emitted in all directions, including upwards to space, and also downwards to the Earth. This downward reradiation warms the Earth's surface, and making it 33°C warmer than it would otherwise be, resulting in an average surface temperature of $+15^\circ\text{C}$ rather than the -18°C , which it would be in

Figure 2.3: A simplified diagram illustrating the greenhouse effect (IPCC,1990)

the absence of the greenhouse gases. The greenhouse effect is a natural process which has already existed for millions of years and is essential to the existence of life on Earth as we know it.

The scientific community is in complete agreement about the fundamental validity of the theory of the greenhouse effect (as argued above), and identifies several pieces of evidence (IPCC, 1990). Firstly, the Earth's surface temperature is about 33°C warmer than it would be in absence of the greenhouse effect, as also confirmed by satellite measurements of radiation emitted through the Earth's surface and through the atmosphere. Secondly, the greenhouse effect is the only basis on which the great differences in atmospheric temperatures and climate between planets like Mars, Venus and the Earth can be explained. Thirdly, measurements from ice cores dating back to 160,000 years ago show that there is a positive corre-

lation between the atmospheric CO₂ concentration and surface temperature changes (see Figure 2.4).

One may wonder why scientists are presently concerned about climate change if changes in climate have already occurred quite frequently in the past. Since the industrial revolution, the carbon dioxide concentration in the atmosphere has increased steadily by about 25%, from 280 ppmv (around 1800) to the highest level ever reached in history, namely: 353 ppmv in 1990 (IPCC, 1990). This increase is fully attributed to human activities such as fossil fuel combustion and deforestation. Not only the atmospheric CO₂-concentration raised rapidly, but atmospheric concentrations of other greenhouse gases have also escalated over that period, as is indicated by data from a global network of monitoring facilities (including ice core measurements). Methane concentrations have more than doubled since pre-industrial

Figure 2.4: CO_2 concentrations (bottom) and estimated temperature changes (top) during the past 160,000 years, as determined on the ice core from Vostok, Antarctica (Barnola et al., 1987). Temperature changes were estimated based on the measured deuterium concentrations (IPCC, 1990).

times (around 1800), partly due to the increasing emissions from rice paddies, coal mining, landfills, dumps, etc. Nitrous oxide concentrations have increased by 8% since 1800, probably due to increasing agricultural activities (fertilizer use). New greenhouse gases have been added to the atmosphere, such as CFCs, which are used as aerosols, as refrigerants, and as blowing agents since the beginning of the 1930s.

Increases in atmospheric concentrations of these radiatively-active gases, as observed over the past centuries, will undoubtedly lead to a net increase in energy input to the lower stratosphere (enhanced greenhouse effect), and hence succeeded by elevation of the global mean surface temperature of the Earth. The only uncertainties concern how much, where, and how fast such temperature increases will occur.

Over and above such growth in atmospheric concentrations of greenhouse gases, there are also other factors which can influence the climate system. The most important natural factors are: variations in the orbit parameters, volcanic activity (aerosols), fluctuations in solar activity, continental drift and natural non-linear interactions between the five main components of the climate

system; the atmosphere, the land surface, the biosphere (the terrestrial biota and the other life-supporting systems on the land and in the ocean), the ocean itself, and the ice caps (IPCC, 1990). Other anthropogenic factors are sulphur emissions from industry, variations in albedo due to deforestation and desertification, changes in tropospheric ozone concentrations and anthropogenic positive/negative feedback mechanisms.

Greenhouse gases

Carbon dioxide contributes to about 50% of the enhanced radiative perturbation and is currently annually rising at about 0.5% (1.8 ppmv) due to anthropogenic emissions. Although carbon in the form of CO_2 , carbonates, organic compounds, etc. is cycled in large quantities between the various reservoirs, atmosphere, oceans, and terrestrial biota (the carbon cycle), the net inputs into the atmosphere from fossil fuel combustion and land use changes (primarily deforestation) albeit much smaller than the natural fluxes are responsible for disturbance of natural balance. The total atmospheric accumulation of CO_2 is regulated by the two main sources mentioned above, and the CO_2 -

uptake by the terrestrial biosphere and the oceans. The source resulting from fossil fuel combustion is well-known (6.0 ± 0.5 GtC/yr in 1990, $\pm 5-10\%$), in contrast with the source resulting from land use changes, about which little is known so that serious uncertainties exist ($\pm 100\%$). The IPCC (1990) estimated the net CO_2 -flux resulting from land use changes over the last decade 1980-1989 at 1.6 ± 1.0 GtC/yr. The uncertainties regarding oceanic and terrestrial sinks are also of the order of $\pm 100\%$. The IPCC 1990 estimate of an annual oceanic uptake of 2.0 ± 0.8 GtC/yr over the last decade is still widely accepted. The role of the terrestrial biosphere as a sink associated with the sequestration via forest generation and the fertilization effect remains a scientific bone of contention. This results in a net imbalance between the sources and sinks of 1-2 GtC/yr, a discrepancy which is also not resolved in the Scientific Assessment supplement issued by IPCC (1992).

Methane levels have doubled since the pre-industrial era, from about 0.8 ppmv around 1765 to the current globally-averaged value of 1.72 ppmv. However, the rate of this atmospheric increase has been slowing down rapidly from about 1.3% (0.02 ppmv) per year in the late 1970s, via about 0.75% per year (0.012-0.013 ppmv) in the 1980s, to as low a rate as about 0.6% (0.01 ppmv) per year (IPCC, 1992; Steele *et al.*, 1992). Methane presently contributes about 15% to current radiative forcing (IPCC, 1990). Major biogenic sources of methane are natural wetlands, rice paddies, landfills, domestic ruminants and biomass burning. Fossil sources include the exploitation of coal and oil reserves and natural gas venting and distribution. The total annual CH_4 emission is about 500 Tg/yr, as deduced from the magnitude of the sinks and the rate of its atmospheric accumulation. The oxidation of methane via hydroxyl radicals is the major sink mechanism, but its magnitude is decreasing as a result of the decreasing atmospheric level of hydroxyl associated with increasing levels of other atmospheric pollutants. Over and above increases in methane emissions themselves, the anticipated fall in global hydroxyl available for removing methane

from the atmosphere will lead to a higher level of methane in the atmosphere. The atmospheric lifetime of CH_4 is currently estimated at about 11 years (IPCC, 1992).

Nitrous oxide levels in the atmosphere are increasing at an annual rate of 0.2-0.3 % (WMO, 1992) and contributes 6% to current enhanced greenhouse effect (IPCC, 1990). The major sink mechanism which eliminates nitrous oxide is photochemical decomposition in the stratosphere, and the compound therefore has a long atmospheric lifetime of about 130 years (WMO, 1992). The observed atmospheric increase is assumed to be the result of man's influence on the nitrogen cycle. The most important sources of nitrous oxide are supposed to be soils, oceans, fertilizer use and forest to grassland/arable land conversion. However, these sources alone do not sufficiently account for the observed imbalance in the rate of atmospheric accumulation.

As well as being ozone-depleting substances, *CFCs*, *HCFCs*, *HFCs*, CH_3CCl_3 , and CCl_4 (*halocarbons*) also belong among the greenhouse gases (as described section 2.2.1).

Ozone is an effective greenhouse gas in the upper troposphere and lower stratosphere. Lower stratospheric ozone has been reduced during recent decades, causing negative ozone forcing as described in section 2.2. By contrast, tropospheric ozone has increased by about 1% yearly over the last few decades at northern middle latitudes.

Precursors of tropospheric ozone (CO , non-methane hydrocarbons (NMHC) and oxides of nitrogen (NO_x)) have both natural and anthropogenic sources. The trend in the level of these tropospheric ozone precursors remains uncertain at present.

2.3.2 Historical development

The first experiment based on heat entrapment due to radiative forcing of trace gases, goes back some 155 years. Fourier (1827) was probably the first to discuss the CO_2 /greenhouse effect by comparing it with what happens to the air trapped under a glass plate. The first scientific indications that mankind is capable of influencing global cli-

mate by increasing atmospheric greenhouse gas concentrations date back almost a century ago. In 1896, Arrhenius (1859-1927), who refers to Fourier's seminal work, was the first who made climate change calculations under elevated CO_2 -level, and found that an increase in atmospheric CO_2 by a factor 2.5-3 would lead to a global mean surface temperature increase of 8-9°C (Arrhenius, 1896).

Studies into the modelling of human interference on the carbon cycle first appeared about twenty-five years ago (Craig, 1957; Revelle and Suess, 1957; Bolin and Eriksson, 1957). At that time, Revelle and Suess (1957) concluded that the detection of the climate change due to human activities could be expected within a few decades. It was also in 1957 that Keeling and others started to measure the CO_2 -concentrations at Mauna Loa (Hawaii) (Keeling and Bacastow, 1977).

International attention began to be paid to the question of climate change in 1979, during a World Climate Conference in Geneva, which had been convened by the WMO (1979). An important outcome of this meeting was an appeal to the world's nations to improve knowledge about climate change, and to foresee the potential changes in climate. After this conference, various countries initiated climate change programmes, such as the Carbon Dioxide Assessment Committee of the US (CDAC, 1983), and the Health Council of the Netherlands (1983).

In preparation for the World Climate Conference of 1990, a series of workshops was held, most of which were organized and sponsored by: the United Nations Environment Programme (UNEP), World Meteorological Organization (WMO), and International Council of Scientific Unions (ICSU). In 1985, the first workshop of the series was held in Villach (Austria). As a result of this workshop, the ICSU launched the International Geosphere Biosphere Program (IGBP) in the following year, with its main objective of describing and understanding the interactive physical, chemical, and biological processes, and the anthropogenic changes characteristic of the Earth system. In 1987, at workshops in Villach and

Bellagio sponsored by the UNEP, WMO, and ICSU, an international group of experts reviewed alternative policies on a range of environmental problems related to climate change (Jäger, 1987). In 1988, at the Conference on the Changing Atmosphere in Toronto (WMO, 1988), scientists and policy-makers formulated several recommendations, including a call for a 20% reduction in carbon dioxide emission reduction by 2005, followed by a global reduction of 50% by around 2025, which would theoretically be sufficient to stabilize atmospheric concentrations (Environment Canada, 1988).

In July 1988, UNEP, WMO and ICSU established the Advisory Group on Greenhouse Gases (AGGG) to pursue issues which had been raised at the Villach workshops in 1985 and 1987 and at the Bellagio workshop in 1987. The primary task of the AGGG was to prepare a report on 'the full range of responses to anticipated climatic change'. Within the framework of the AGGG, three working groups were set up: Working Group I to analyse limitations strategies; Working Group II to identify targets and indicators of climate change, and Working Group III to evaluate costs of adaptation and limitation strategies. The work was coordinated by the Stockholm Environment Institute in Sweden, and the results were presented in 1990 (AGGG, 1990a, 1990b, 1990c, and 1990d).

In parallel to these initiatives, in November 1988 the Intergovernmental Panel for Climate Change (IPCC) was established by WMO and UNEP to provide a forum for scientific and political discussions and policy preparation (Nitze, 1989). This panel similarly set up three working groups: Working Group I to provide a scientific assessment of climate change; Working Group II to provide an assessment of the potential impacts of climate change, and Working Group III to consider response strategies. The results generated by all three groups were presented at the Second World Climate Conference in October/November 1990. This IPCC First Assessment Report comprises the IPCC Scientific Assessment by Working Group I (IPCC, 1990), the IPCC Impacts Assessment of Working Group II (IPCC, 1991a), and the

IPCC Response Strategies discussed by Working Group III (IPCC, 1991b). The Scientific Assessment Report of IPCC (1990) is the most authoritative and strongly-supported statement on climate change that has ever published by the scientific community, and has become a standard work of reference, which is widely used by policy-makers, and scientists.

The Report had a major impact in the development of an international climate convention. The scientists and politicians participating at the conference emphasised that an immediate global response to the climate change issue was required, enabling all countries to achieve sustainable development, and that preventive actions should be taken on the basis of current knowledge. The conference did not issue any explicit statements about the reduction of greenhouse gas emissions (SWCC, 1990a; 1990b).

After the Second World Climate Conference, the United Nations General Assembly (UNGA) commissioned the International Negotiation Committee (INC) to prepare an international agreement in response to anticipated climate change (UNGA, 1991). Their results were presented at the United Nations Conference on Environment and Development (UNCED) at Rio de Janeiro in June 1992.

At the same time, the IPCC was asked to produce updates of their 1990 Reports, and to provide the conference and the ongoing negotiations on the Framework Convention on Climate Change with the latest information on climate change. The IPCC's Working Group I produced an update of the IPCC Scientific Assessment (IPCC, 1992), and a number new findings concerning the problem, have come to light, as summarized in the IPCC's Supplement report (IPCC, 1992). The major new findings are:

- rates of increase in atmospheric concentrations of most greenhouse gases have recently been continuing unabated, although the rates have slowed down in the case of methane and some of the halogen compounds.
- during the last decade, ozone depletion in the lower stratosphere at middle and high latitudes induces radiative forcing, which,

globally-averaged, could counteract the positive direct radiative forcing associated with CFCs.

- to some extent the cooling effect of aerosols from sulphur emissions may also have significantly offset global warming in the Northern Hemisphere during recent decades.

The latter two mechanisms have probably partially counteracts hitherto induced greenhouse warming, and should therefore be incorporated in contemporary climate models in order to obtain more reliable estimates of climate sensitivity (long-term change in surface air temperature following a doubling of CO₂ levels), and climate change projections.

In anticipation of UNCED in Rio de Janeiro, the participants in the INC, UN member states, a number of international organisations and non-governmental organisations, were trying to reach a legally-binding agreement. At the same time, European Community energy and environmental ministers had already adopted a concrete quantitative target, according to which CO₂ emissions were to be stabilized at 1990 levels by the year 2000. As a basic instrument with which to achieve this target, the energy/CO₂ tax was proposed. The tax is to be levied from 1 January 1993 at 3 US dollars per barrel oil, and subsequently increased by one dollar annually till 2000. Exceptions will possibly made for a number of energy-intensive sectors, as long as their major trading partners such as Japan and USA have not adopted similar regulations.

Despite all good intentions expressed at UNCED, the initially proposed reduction targets were toned down as time went by, and finally, the UNCED's intensification declaration: Climate Change Convention (INC, 1992), was formulated as call to achieve a stabilization of greenhouse gas concentrations in the atmosphere, and thus implicitly sets a limit to the emissions of those gases. The text does not exactly specify when, and at which level concentrations of greenhouse gases would have to be stabilized, or what the implementations would be for global emissions. This declaration is presently signed by by all key nations, including the

United States, Great Britain, and Japan (INC, 1992).

2.3.3 Modelling climate change

A broad range of climate models has hitherto been developed.

Energy Balance Models (EBMs) calculate surface temperature change on the basis of the assumption that net heat remains unchanged (Budyko, 1969; Sellers, 1969; Wigley and Schlesinger, 1985; Jonas *et al.*, 1992).

Radiative Convective Models (RCMs) are designed to calculate temperature, humidity and radiation in a vertical direction.

However, the most sophisticated climate models are the General Circulation Models (GCMs), which consist of numerous mathematical equations describing atmosphere, ocean and land surface processes in the light of the laws of physics. Simplified parameterizations have been used to incorporate processes such as cloud formation and the behaviour of deep ocean currents. In a GCM, the Earth is divided into gridboxes of 200 by 500 km horizontally, and each gridbox is vertically divided into 9-12 layers. GCMs can simulate nearly all of the climatic variables which determine our daily weather (temperature, precipitation, wind, cloud-cover, radiation, and soil humidity). A summary of the GCMs which are currently available can be found in IPCC (1992). Supplementary to the GCMs are the 'Coupled' General Circulation Models (CGCM) which are coupled ocean/atmosphere circulation models. Four CGCM models are currently (1993) available: National Centre for Atmospheric Research (NCAR), USA; Geophysical Fluid Dynamics Laboratory (GFDL), USA; Max Planck Institute (MPI), Germany; Meteorological Office (UKMO), UK). GCM/CGCM models are usually concerned to predict the equilibrium surface temperature increase following a doubling of carbon dioxide levels (called climate sensitivity). The range of climate climate sensitivities

given by the IPCC (1990) and re-affirmed in IPCC (1992), is between 1.5 and 4.5°C, with the central estimate value of 2.5°C. The major source of uncertainty in the predicted changes are the radiative effects of clouds and their related processes. These models have hitherto incorporated radiative forcing associated with greenhouse gases, but not other factors such as aerosols. Major improvements in predictions of future climate change can be achieved by incorporating radiative forcing from sulphate aerosols and ozone depletion into the present GCMs (and CGCMs). In place of the usual equilibrium simulation runs, transient runs on CGCMs have recently set up. In a transient run, the time-dependent climate response is simulated according to steadily increasing greenhouse gas concentrations. For example, the new simulation run for the IPCC 1990 Business-as-Usual scenario with a CGCM (not including the radiative effects of ozone depletion and aerosols) shows a future warming rate of 0.3°C per decade (IPCC, 1992). A description, and comparison of results of, the four CGCM models can be found in World Climate Research Programme (WCRP, 1992).

2.4 Interactions between climate change and ozone depletion

The problems of climate change and stratospheric ozone depletion are interrelated, not only by virtue of their common sources, but also as a consequence of the numerous interactions between the two. These interactions can be direct or indirect, and occur according to tropospheric chemistry (see *Figure 2.5*) (German Bundestag, 1989).

Two direct interactions (over and above their common sources, (*d3*) in the *Figure*) are distinguished. The importance of the first direct interaction, a negative radiative forcing due to ozone depletion (*d1*), was recently demonstrated in model studies conducted by Ramaswamy *et al.* (1992) and the WMO (1992). Both studies show that depletions of

Figure 2.5: Interactions between climate change and stratospheric ozone depletion

ozone in the lower stratosphere during the last decade have caused reductions in the radiative forcing occurring in the surface-troposphere system at middle and high latitudes, which could, on a global scale, be equal in magnitude, but opposite in sign to the enhanced direct halocarbon radiative forcing. The importance of the second interaction, namely: the atmospheric increases of greenhouse gases and their resulting tropospheric warming and stratospheric cooling will affect the ozone concentrations in the stratosphere. The decrease in stratospheric temperature slows down the rate of ozone destruction induced by chemical reactions (d2).

However, most interactions are indirect. The increase in UV-B radiation due to stratospheric ozone depletion might negatively affect the phytoplankton population, which reduces the CO₂-uptake in the oceans (i1 in

Figure). The latter will result in an increase of atmospheric carbon dioxide, and therefore contribute to the global warming. Stratospheric ozone depletion is accelerated by catalytic cycle reactions involving the catalysts NO_x, H and OH (see paragraph 2.2.1) (i2). Moreover stratospheric ozone depletion influences the column of ozone, and thus the tropospheric chemistry (i3). The formation of tropospheric ozone, which is a greenhouse gas, is of importance for the enhanced greenhouse effect (i4). Furthermore, there are several temperature feedbacks, involved in the interactions between the systems, such as the temperature feedbacks pertaining to the tropospheric chemistry, and especially to the reaction rate coefficients (i5). Finally, the emissions of CO, NO_x and CH₄ influence the processes within the tropospheric chemistry, which indirectly affect both environmental problems.

Part II Methodology

3 Methodological framework: IMAGE

3.1 Introduction

The integrated, interdisciplinary modelling framework described here is the policy-oriented model: IMAGE (experimental version 1.6)^[1], which consists of the integrated climate assessment model IMAGE (version 1.6), and the UV-B chain model.

IMAGE (version 1.6) is a climate assessment model which links the scientific data and knowledge with policies aimed at controlling and mitigating the effects of climate change. More specifically, IMAGE is a simulation model designed to develop scenarios of greenhouse gas emissions and to calculate and evaluate their effects on global mean temperature and sea level rise, and on ecological and socio-economic aspects of specific regions. In essence, IMAGE is designed to simulate the entire cause-effect relationship with respect to climate change. It represents an integration of the present 'state-of-the-art' knowledge (including the present-day uncertainties) and expertise from the different scientific disciplines in the field of climate change such as global economics, atmospheric chemistry, marine and terrestrial biogeochemistry, ecology, climatology, hydrology, and glaciology, and thus does not claim to be more than a simplification of reality (Rotmans, 1990).

The original version of this model, IMAGE (version 1.0) is extensively described in Rotmans (1990). The version of IMAGE used here is broadly similar to the IMAGE model incorporated in the ESCAPE

model (CRU, 1992a; CRU, 1992b, Rotmans *et al.*, 1993), with the exception of the methane model. A regionalized version 2.0 of IMAGE with more detailed, process-oriented submodels has been developed, and is described in Alcamo *et al.* (1994).

The recently developed integrated UV-B chain model (coupled halocarbon/UV-B impact model) describes the entire cause-effect relation chain pertaining to the ozone issue, starting with the production and consumption of the CFCs and other halocarbons, to the human health effects in terms of skin cancer incidence in two specific regions: the Netherlands and the United States (Slaper *et al.*, 1992). This model was integrated into IMAGE (version 1.6), thus creating IMAGE (experimental version 1.6).

This modelling framework now consists of a suite of linked models (modules); a world energy/economy model, land use change model, atmospheric chemistry model, halocarbon model, carbon cycle model, climate model, sea level rise model, a UV-B impact model and a socio-economic impact model. In view of the accumulation of uncertainties inherent in an integrated modelling approach, IMAGE (experimental version 1.6) is an interpretive tool rather than a predictive tool, and is primarily intended to enhance our insights into the present and future forces, which affect global climate change and stratospheric ozone depletion.

The structure of this Chapter is as follows: section 3.2 describes the different perspectives from which the system structure of the model can be viewed, related to the type of user involved (policy-maker, specialist, generalist, etc.). Although not aiming to provide a complete overview of all perspectives of the system structure of the IMAGE model (experimental version 1.6), this section describes the perspectives

[1] The methodological framework, IMAGE (experimental version 1.6), described here represents the view of the author only, and is not an official version of the IMAGE model which can be supported by the RIVM. The UV-B chain model will be available as an independent model in the course of 1993, and thereupon enjoy RIVM approval.

employed hitherto: the model-structure perspective, the reservoir structure perspective, and the mathematical system perspective. Section 3.3 describes the mathematical formulation of the dynamic system. Section 3.4 offers a brief description of the different modules employed in IMAGE (version 1.6), focusing on the differences vis-à-vis the original version of IMAGE, version 1.0. Finally, section 3.5 concludes this Chapter.

3.2 Perspectives of the system structure

3.2.1 Model system perspective

In Rotmans (1990) IMAGE (version 1.0) is seen as a concatenation of autonomously functioning models, which is referred to as the model structure perspective. In this perspective, the version of IMAGE described here consists, at the highest aggregation

level, of: a world energy/economy model, a land use change model, a carbon cycle model, an atmospheric chemistry model (a coupled methane and N_2O model), a climate model, a sea level rise model, a halocarbon model, a UV-B impact model and a socio-economic impact model (*Figure 3.1*). Each of the models describes a separate modelling field of climate change and stratospheric ozone depletion, and is a simpler version of more elaborate multi-dimensional models, developed by specialists in this field. For this reason, this perspective is especially suitable as a communication tool between the model-builders of IMAGE (experimental version 1.6) and the specialists, although it cannot provide many insights into the fluxes and transport processes between and within the five compartments of the climate system, and their contents.

The models are linked in a simple manner, the output of one module serving as an input to the next. The output and input,

Figure 3.1: Model structure perspective of IMAGE (experimental version 1.6)

denoted by arrows, can either be forcing functions (emissions), or processes (ozone depletion, radiative forcing), or state variables (concentration, temperature, sea level), and therefore, the notation of the model system perspective is not homogenous.

At a lower aggregation level, each model is itself constructed modularly. *Figure 3.2* depicts the modular structure of the IMAGE model at this aggregation level.

3.2.2 Reservoir structure perspective

In reality, the Earth's climate system consists of five subsystems (which act as reservoirs): the atmosphere (the troposphere and the stratosphere), the land surface (including areas of human habitation), the terrestrial biosphere (including land-based biota), the ocean (the surface waters and the deep ocean) and the cryosphere (ice) (IPCC, 1990). The chemical and physical status of this system can be characterized by the following elements (Rodhe, 1992):

- the contents and turnover times in the various components;
- the transport and transformation processes between and within the components, many of which are of a cyclic nature: the fluxes between and within the components.

The rate of transfer of material between the climate system components, depends on the contents of the reservoirs, while the physical and chemical characteristics of the components are also of importance.

The climate system can be represented by the reservoir structure perspective adopted by IMAGE. From this perspective, IMAGE is seen as a simulation model that couples the five reservoirs of the climate system, and integrates the interacting fluxes (transport and transformation processes) (*Figure 3.3*). Between and within these reservoirs, the following key processes can be distinguished: fluxes of chemical substances (gases) between reservoirs, atmospheric chemical processes, radiative perturbation, UV-B radiation changes, temperature increase, and sea level rise. An advantage of this approach is that it yields more insights into the fluxes, reservoir contents, and turnover times, and it answers questions such as: where does the

pollution come from, and where is the pollution going next? Therefore, this representation of the model is of interest to all kinds of users, whereby the user's knowledge of, and the interest in, the environmental problem determines the choice of the aggregation level.

The notation of the reservoir structure perspective (*Figure 3.3*) is more homogenous than that of the model system perspective, since in this Figure the bold-faced arrows denote forcing functions, and the other arrows describe processes.

3.2.3 Mathematical system perspective

In Braddock *et al.* (1993) the IMAGE model (version 1.0) is described as a mathematical system: a dynamic system of 151 differential and 9 algebraic equations, linking all state variables. The dynamic system is of the form:

$$\begin{aligned} \frac{d}{dt} X(t) &= AX(t) + NX(t) + U(t) \\ X(t_0) &= X_0 \end{aligned} \quad (3.1)$$

This formulation is known as a dynamic control system. The time dependent vector $X(t)$ ($= (X_1(t), \dots, X_n(t))^T$) represents the state of the system at time t ; and $U(t)$ the control function at time t (here the emissions of greenhouse gases and ozone depleting substances). The time t_0 is the initial time from which the system is analysed. The vector $X(t_0)$ is the state of the system at time t_0 . The terms $AX(t)$ and $NX(t)$ are the linear and nonlinear components of the system, respectively. The major non-linearities of the system of equations arise from radiative forcing by the greenhouse gases and ozone depleting substances, the equilibrium concentrations of carbon in the surface layers, and the net primary production of the ecosystems.

The main advantage of the mathematical perspective is that it enables various mathematical aspects to be investigated, e.g. stability of the model (it was demonstrated that the model was stable), possible equilibrium points of the mathematical system (which were not found), response times of the model to changes in the inputs arrived at by consid-

Figure 3.2: an Integrated Model to Assess the Greenhouse Effect (IMAGE) (experimental version 1.6)

Figure 3.3: Reservoir structure perspective of IMAGE (experimental version 1.6)

ering the eigen values of the system (response times varied from 1 to 500 years (Braddock *et al.*, 1993). This view of the system is only of interest to specialists, especially mathematicians, and need not be referred to hereafter.

3.3 Mathematical formulation of the dynamic system

The problem of climate change and ozone depletion is modelled in IMAGE (experimental version 1.6) as a dynamic system featuring discrete six-monthly time steps and a simulation period of 200 years, from 1900 to 2100. The year 1900 symbolizes the end of the pre-industrial era, and is assumed to have been a 'steady-state' situation at that time.

The mathematical formulation of this system, as well as the calculation procedure, is per definition independent of the system perspective, and can be described as follows:

The state of the system at an arbitrary point in time t is represented in mathematical terms by a vector of state variables $X(t) = (X_1(t), \dots, X_{n1}(t))^T$. The choice of the state variables is crucial to the model structure. The physical, chemical, radiative, biological, and transfer processes are described by means of mathematical equations in terms of forcing functions (emissions) $U(t) = (U_1(t), \dots, U_{n2}(t))^T$ and state variables. The processes are expressed as $P(t) = (P_1(t), \dots, P_{n3}(t))^T$, with $P_j(t)$ or $P_j(t, X_1(t), \dots, X_{n1}(t), U_1(t), \dots, U_{n2}(t))$ ($j=1, \dots, n3$). The 'steady-state' situation at the initial time is written by X_0 . In each iteration step of a simulation run, the subsequent state

of the reservoir $X(t+\Delta t)$ is described as a function of the previous state ($X(t)$), the processes involved $P_j(t)$ ($j=1,\dots,n3$) and the forcing functions, where Δt is the discrete time step of the dynamic system.

3.4 Description of the IMAGE modules

In this section, the various IMAGE (experimental version 1.6) submodels (see *Figures 3.1* and *3.2*), are described briefly. Submodels which have been modified since the original version of IMAGE (Rotmans, 1990), are indicated by an asterisk (*) in the text, and in *Figure 3.2* the differences appear explicitly.

3.4.1 Emission models: the energy/economics model and the land use model

The emission models, extensively described in Rotmans (1990), simulate the historical, present and future emissions of the greenhouse gases CO_2 , CH_4 , CO and N_2O , while halocarbon emissions are simulated by the halocarbon model. The emission models employ the world energy/economics model and the land use model. The world energy/economics model, based on Edmonds and Reilly (1986), simulates the energy-related emissions of CO_2 , CH_4 , CO and N_2O , while the land use model calculates the greenhouse gas emissions of the other sources related to land use changes, agricultural activities, land fills and natural sources. The part of the land use change model which pertains to CO_2 emissions from land use changes is described in Rotmans and Swart (1991), and will shortly be discussed in Chapter 6. The global annual estimates of historical emissions of all greenhouse gases for the period 1900 to 1991 have been incorporated in the model. For the future emissions of the greenhouse gases over the period 1992 to 2100 the user can either interactively construct a tailor-made emission scenario using the emission models, or choose from among fixed emission scenarios as developed by IPCC.

3.4.2 The carbon cycle model*

The carbon cycle model featured in IMAGE (version 1.6) is an extended version of the model constructed by Goudriaan and Ketner (1984), and simulates the concentrations of CO_2 in the various components (the atmosphere, the terrestrial biosphere and the ocean). The model consists of an ocean box-diffusion model, a terrestrial biosphere model and an atmospheric box model. Two versions of the carbon cycle model have been developed: a stand-alone version starting in 1760, and assuming an initial steady state before anthropogenic disturbances are imposed upon the system; and an integrated version incorporated in the IMAGE framework starting in 1900, incorporating the initial CO_2 concentrations in the various compartments based on the calculations derived from the stand-alone version. The ocean box-diffusion model is a slightly modified version of Goudriaan and Ketner's (1984) model, and is described in detail in Rotmans (1990). The details of the terrestrial biosphere model and the atmospheric model are also described in Rotmans (1990).

The main difference which distinguishes our carbon cycle model from that employed in IMAGE (version 1.0) (Rotmans, 1990) is the incorporation of biogeochemical feedbacks, which in this case are the following terrestrial feedbacks: the relation between elevated CO_2 and net primary production (the CO_2 -fertilization effect); the temperature effects on net primary production and on the respiration of soil and litter, and the following oceanic feedbacks: the oceanic feedback associated with vertical diffusion and an ocean temperature/chemistry feedback. In den Elzen and Rotmans (1993a; 1992a) and Rotmans and den Elzen (1993b) a description is given of the modelling backgrounds and assumptions of the various oceanic and terrestrial biogeochemical feedbacks which are incorporated in the model. Rotmans and den Elzen (1993b) have evaluated the role of several biogeochemical feedbacks in balancing the carbon budget for the period 1760-1990, by varying model parameters which represent the terrestrial feedback processes. Simulation experiments with the carbon

cycle model show that ignoring these feedbacks results in an apparent imbalance between the sources and sinks of CO_2 . Thus, the modelled feedback mechanisms act as sinks for the terrestrial biosphere, and are predominantly associated with the CO_2 -fertilization effect. As opposed to most carbon cycle models used by the IPCC (which ignore such feedback processes), the carbon cycle model of IMAGE (experimental version 1.6) envisages a balanced carbon budget for the period 1760-1990. Chapter 6 sets out the methodology of balancing the carbon budget using the terrestrial feedbacks. This Chapter being entirely based on Rotmans and den Elzen (1993b).

3.4.3 The atmospheric chemistry model*

The atmospheric chemistry model incorporated in IMAGE (experimental version 1.6) comprises the methane model and the N_2O model. The atmospheric chemistry model simulates the concentrations of the greenhouse gases CH_4 , N_2O , O_3 (tropospheric, column and upper stratospheric ozone), CO , NO_x , OH , and stratospheric NO_y .

The methane model*

The essential element in the atmospheric chemistry model is the methane model, which comprehensively simulates key processes in the global CH_4 -CO-OH cycle. This photochemical tropospheric model is described in Rotmans *et al.* (1992) and in Krol and van der Woerd (1994). The methodology is the same as that used in the original IMAGE methane model (Rotmans, 1990), but more processes are included, related to the emissions and concentrations of the compounds: OH , NO_x , NO_y , and O_3 .

The methane model is a box model which is designed to chart globally-averaged atmospheric concentrations of methane, carbon monoxide and hydroxyl. This is achieved by simulating the main atmospheric chemical processes influencing the concentration of these gases using suitably globally-averaged descriptions of those processes. This straightforward approach is essentially an interpretation of the one, two and three

dimensional photochemical models simulating the CH_4 -CO-OH cycle (Bruhl and Crutzen, 1988; Thompson and Cicerone, 1986; Isaksen and Hov, 1987). The major sink mechanisms incorporated in the model are the oxidation by hydroxyl radicals and the uptake by soils. In the model, the production of hydroxyl is dependent on the concentration of nitrogen oxides, tropospheric ozone, water vapour and on the total column of ozone (Prather *et al.*, 1988). Changes in tropospheric ozone are dependent on the concentrations of methane, carbon monoxide, nitrogen oxides and the total column of ozone. The chemical rate coefficients are calculated by taking global averages of local rates (Krol and van der Woerd, 1994). The total ozone column is parameterized by incorporating the concentration of stratospheric chlorine (the main cause of ozone losses at middle and high latitudes): the relation is linear for chlorine concentrations exceeding a certain threshold level (equal to the modelled stratospheric chlorine level in the late 1970s).

Just as carbon cycle feedbacks, methane feedbacks are also built into IMAGE (experimental version 1.6) in a simplified, globally-oriented manner. Some of the climate feedback mechanisms are related to increased microbiological activity in natural wetlands and rice paddies, the feedback caused by destabilisation of methane hydrates in ocean sediments and the feedback involving tropospheric ozone, as described in den Elzen and Rotmans (1993a) and den Elzen *et al.* (1991). The additional release of methane associated with both wetlands and rice paddies is modelled by parameterizing the relationship between methanogenesis and temperature by a Q_{10} -value that reflects the rate of increase of methanogenesis in the event that global temperature rises by 10°C . As a consequence of the modelled feedbacks, the methane model is run in two modes, namely: the reference case and the feedback case. A detailed description of the methane model is given in Chapter 7.

The N_2O model*

The N_2O model simulates the atmospheric N_2O concentration. In reality, N_2O is stable

in the troposphere and is destroyed in the stratosphere by photodissociation and by the reaction with single oxygen. N_2O is removed very slowly from the atmosphere, and, according to the WMO (1992), has an average atmospheric lifetime of 110-168 years. The nitrous oxide concentration is calculated using the mass balance equation, whereby the removal process in the stratosphere is proportional to the atmospheric concentration and inversely proportional to the atmospheric lifetime of N_2O :

$$\frac{dC_{N_2O}(t)}{dt} = ca_{N_2O}E_{N_2O}(t) - C_{N_2O}(t)/L_{N_2O} \quad (3.2)$$

where $dC_{N_2O}(t)/dt$ is the change in atmospheric N_2O concentration (ppbv/yr), ca_{N_2O} is the conversion factor of N_2O (ppbv/TgN), $E_{N_2O}(t)$ is the level of global N_2O emissions (TgN/yr), and L_{N_2O} is the atmospheric lifetime of N_2O (yr), whereby the latter is here assumed to be constant. The lifetime is determined at 150 years, based on the mass balance calculations derived from Equation (3.2) and incorporating the currently-observed atmospheric growth rate of about 3 to 4.5 TgN, as well as the total 1990 emissions of 12.9 TgN (Pepper *et al.*, 1992), and the present-day atmospheric concentration of N_2O of 310 ppbv (Watson *et al.*, 1992). This lifetime corresponds with the lifetime estimated by IPCC (1990).

The methodology for calculating the N_2O concentration differs from the method of the exponentially delayed emissions, as described in Rotmans (1990). Using the Rotmans' calculation method, a lifetime of 170 years is necessary to reproduce the concentration trend in 1990. This lifetime corresponds with the upper limit of the range of lifetimes as estimated by the WMO (1992), and far exceeds the rather low central estimate of 130 years arrived at by the IPCC (1992).

3.4.4 The halocarbon model*

The halocarbon model simulates halocarbon concentrations, and the resulting atmospheric chlorine concentration and radiative effects

due to the halocarbons (Elzen *et al.*, 1992b). In complexity, the model is similar to Prather *et al.*'s (1992), except for four main elements: (i) the production and consumption of halocarbons is disaggregated into nine regions: USA, EC, Japan, other OECD countries, Eastern Europe, the GOS, China, India and other developing countries; (ii) the time-lag between halocarbon production and emission is regarded as being dependent on the end-use category, an approach based on Wigley (1988); (iii) the incorporation of direct radiative forcing and atmospheric concentration relationships; (iv) an incorporation of the relationship between indirect radiative effects and atmospheric chlorine concentrations, following Wigley and Raper (1992). A brief description of the model is found in this section (a detailed description will follow in Chapter 10). At present, the halocarbon model includes the following halocarbons: five CFCs (CFC-11, CFC-12, CFC-113, CFC-114, CFC-115), methylchloroform (CH_3CCl_3), carbon tetrachloride (CCl_4), HCFC-22, three imaginary substitutes (HCFC-X, HCFC-Y and HFC-Z), two halons (halon-1211, halon-1301), CH_3Cl and CH_3Br . The three imaginary compounds were chosen to represent a class of alternatives (H(C)FCs): HCFC-X, the class of HCFCs with an Ozone Depletion Potential (ODP) greater than 0.05, whereby the ODP of CFC-11 is equal to 1) (HCFC-141b, HCFC-142b); HCFC-Y, the class of HCFCs with an ODP lower than 0.05 (HCFC-123, HCFC-124, HCFC-225); and HFC-Z with an ODP of zero, the class of HFCs (HFC-125, HFC-134a, HFC-143a, HFC-152a), in the sense that they share the average properties of these gases with respect to atmospheric lifetime (stratospheric and tropospheric lifetimes), number of chlorine atoms per molecule, ODP and Global Warming Potential (GWP).

The concentrations of the CFCs and CCl_4 are now calculated in a manner analogous to Equation (3.2). The halocarbons: CH_3CCl_3 , HCFC-22 and the three imaginary alternatives (denoted as *alt*) are destroyed in the troposphere by the reaction with OH, their concentration is now described as:

$$\frac{dC_{alt}(t)}{dt} = ca_{alt}E_{alt}(t) - C_{alt}(t)[1/tL_{alt} + k_{alt}C_{OH}(t)] \quad (3.3)$$

where $dC_{alt}(t)/dt$ is the change in atmospheric concentration of the halocarbon *alt* (pptv), ca_{alt} is the conversion factor (pptv/Mkg), $E_{alt}(t)$ is the global level of emissions of the halocarbon *alt* (Mkg/yr), sL_{alt} is the stratospheric lifetime of the halocarbon *alt* (Prather *et al.*, 1992) (yr), k_{alt} is the rate coefficient of the halocarbon for the reaction with OH, which is equal to $(C_{OH}(1990).tL_{alt})^{-1}$ (ppmv⁻¹ yr⁻¹), and $C_{OH}(t)$ is the globally-averaged tropospheric OH concentration (ppmv) (as calculated by the atmospheric chemistry model), and tL_{alt} is the tropospheric lifetime of the halocarbon *alt* (Prather *et al.*, 1992) (yr).

Finally, the halocarbon model calculates the atmospheric chlorine concentration (taking into account the number of chlorine atoms per molecule of the halocarbon), and the overall radiative forcing, caused by changes in concentrations of halocarbons. Radiative forcing consists of direct forcing associated with halocarbon concentration changes, and indirect forcing due to stratospheric ozone losses. The indirect radiative forcing is a potentially important feedback on the overall radiative forcing due to halocarbons, and has been called stratospheric-ozone-depletion feedback (Wigley and Raper, 1992). This ozone forcing is modelled in a manner similar to that adopted by Wigley and Raper (1992), i.e. parameterized by the concentration of stratospheric chlorine: the relation is linear for chloride concentrations exceeding a certain threshold level, and non-existent below this level. Simulation experiments with the halocarbon model can also be done under two different modes: the base case (ignoring this feedback) and the feedback case.

3.4.5 The climate model

The climate model is an energy balance box upwelling-diffusion model, based on Wigley and Schlesinger (1985) and Wigley and

Raper (1987), and described in Rotmans (1990). The input of the model is the induced radiative perturbation (forcing) due to the changes in the concentration of the different greenhouse gases, as computed according to the expressions given in Shine *et al.* (1990). The climate model includes a land box, an ocean box and atmosphere boxes for atmosphere over land and over oceans (Rotmans, 1990). The basic equation in the energy balance box upwelling-diffusion model is the following:

$$C_m \frac{d\Delta T_o(t)}{dt} = \Delta Q_{tot}(t) - \lambda \Delta T_o(t) - \Delta F(t) \quad (3.4)$$

where C_m is the heat capacity of the mixed layer (W.yr.m⁻²°C⁻¹), $\Delta T_o(t)$ is the change in temperature of the ocean mixed layer (°C), $\Delta F(t)$ is the change in heat flux at the bottom of the mixed layers (W/m²), and λ is the climate sensitivity parameter (Wm⁻²°C⁻¹). The climate sensitivity parameter is calculated as $\Delta Q_{2xCO_2}/\Delta T_{2xCO_2}$, where ΔQ_{2xCO_2} is the radiative forcing for a doubled atmospheric CO₂ concentration, with a value of 4.3 W/m² (Hansen *et al.*, 1988), and ΔT_{2xCO_2} is the climate sensitivity, specified by the global-mean temperature change for a doubled atmospheric CO₂ concentration, with a central estimate of 2.5°C (range: 1.5-4.5°C) (IPCC, 1992). This central estimate is lower than the estimate of 3°C, which was adopted in Rotmans (1990). Another difference vis-à-vis the IMAGE (version 1.0) climate model (Rotmans, 1990) is the modelling of vertical upwelling, with an upwelling coefficient *w* of 4 m/yr (IPCC, 1990).

3.4.6 The sea level rise model

In the sea level rise model, the complex processes of ocean expansion, glacier melting and ice cap dynamics are represented by simple dynamic relationships for the basic processes related to sea level rise: thermal expansion of ocean water, the melting of alpine glaciers, and ablation of the Greenland ice cap, accumulation of ice in the Antarctic, and a natural trend in sea level fluctuation, based on Oerlemans (1989), and described in detail in Rotmans (1990).

3.4.7 The socio-economic impact model

The socio-economic impact model calculates the socio-economic impact of the sea level rise for three kinds of coastal defence systems, namely dikes, dunes, and intertidal areas, and for four water management and water supply sectors, namely saline intrusion, seepage, drainage, and the maintenance of the IJssel Lake. The model is described in detail in den Elzen and Rotmans (1988; 1992b).

3.4.8 The UV-B impact model*

The UV-B impact model is part of the UV-B chain model (coupled halocarbon/UV-B impact model). As input it uses the atmospheric chlorine concentrations (derived from the halocarbon model), and calculates stratospheric ozone depletion, increased UV-B radiation, and skin cancer risks due to increased UV-B radiation associated with ozone depletion for the Netherlands and the United States. The modelling of regional stratospheric ozone depletion is similar to the calculation of the column ozone, i.e. linearly-dependent on the global atmospheric chlorine concentration, with parameters which are found by fitting the modelled ozone trend over the last decade with the observed TOMS data (Stolarski *et al.*, 1991). The relationship between annual carcinogenic effective UV-dose and ozone depletion is based on a regression analysis using the atmospheric UV-transfer model (Leeuw, 1988), see Slaper *et al.* (1992). Finally, the basic equation for the calculation of cumulative skin cancer incidence $Y(\Delta O, \phi, t, a)$ (cases per million) for persons in age group a at time t at latitude ϕ is a function of life-long cumulative effective UV-B exposure $\sum_a E(\Delta O, \phi, a, t)$ of a person's age a (mJ/cm²) at time t , and described as (Slaper *et al.*, 1992):

$$Y(\Delta O, \phi, t, a) = \gamma \sum_a E(\Delta O, \phi, t, a)^c a^{(d-c)} \quad (3.5)$$

where the effective UV exposure is a fraction $\beta(a)$ of the actual effective dose of solar UV-radiation, dependent on the generalized exposure habits of the persons belonging to

age group a , where γ is the calibration coefficient, which is estimated according to the present incidence of each skin cancer type, the sensitivity of the population, and the skin area exposed, and is estimated on the present incidence (cm²/(year.mJ)), where ϕ is equal to 52°N for the Netherlands, or 40°N as the averaged latitude for the United States of America (the two regions considered in the model), where t varies over the period 1990 to 2100 (simulation period of this impact model), and where c and d are skin cancer type dependent model parameters describing the dose dependence and age dependence, respectively. Two types of skin cancer are considered: non-melanoma skin cancer and melanoma skin cancer. The first is subdivided into basal cell carcinoma and squamous cell carcinoma. The populations of the Netherlands and the United States are divided into twenty age groups at five year intervals. The UV-B impact model is described in detail in Chapter 13.

3.5 Discussion

Policy-makers, who are not only charged with identifying possible national response strategies to climate change but also with negotiating international conventions and protocols, need a tool which enables them to estimate the implications of a wide range of policy options for climate change and which can provide a concise overview of the uncertainties surrounding global climate change. The IMAGE model, despite all its deficiencies and limitations, is intended to be such a scientific policy-oriented model.

Hitherto, IMAGE (version 1.0 and 1.6) has been used extensively to assess various global climate strategies in the national context of Dutch environmental studies over the last three years (Langeweg, 1989; RIVM, 1991, 1993), and also internationally within the framework of the IPCC (IPCC, 1991b), and the AGGG (Rotmans *et al.*; 1990a). Moreover, IMAGE (version 1.6) has recently been used as a core element of the ESCAPE interactive climate change assessment model (the Evaluation of Strategies to address Climate change by Adapting to and

Preventing Emissions) which was specially developed for the Directorate General for Environment, Nuclear Safety and Consumer Protection (DGXI) of the Commission of the European Community (CRU, 1992a, 1992b; Rotmans *et al.*, 1993). In addition, the working of the model has also been extensively demonstrated to policy-makers, specialists, and non-specialists.

The other component of IMAGE (experimental version 1.6), namely: the UV-B chain

model, has, despite its relatively short history, already proved itself to be a useful tool for evaluating long-term halocarbon consumption strategies (RIVM, 1993). In the framework of the UNEP conference of the Montreal Protocol Parties in Copenhagen in 1992, different variants of the Copenhagen Amendments were recently assessed for the benefit of the Dutch ministry of housing, physical planning and environment.

Part III Uncertainty Analysis

4 Introduction

4.1 Uncertainties in general

Part III deals with the first objective of this study, namely: to identify and analyse (some of) the present main uncertainties and/or lacunae in knowledge in the fields of climate change and stratospheric ozone depletion. Both problems are beset with many sources of uncertainty which, for the purpose of this study, are separated into two categories (Granger and Henrion, 1990; Rotmans, 1993):

1. '*scientific uncertainties*': i.e. those which arise from the degree of unpredictability of global environmental change processes which may be narrowed down as a result of further scientific research and more sophisticated modelling;
2. '*social and economic uncertainties*': i.e. those which arise from the degree of unpredictability of future geopolitical, socio-economic and demographic developments which are inherently 'unknowable' or unpredictable in practical terms.

This Chapter first presents an overview of current uncertainties, subdivided into these two categories, for the problems of climate change and stratospheric ozone depletion (sections 4.2 and 4.3). Section 4.4 then briefly describes the techniques of sensitivity and uncertainty analysis which, in this study, are used to analyse the influence of uncertainties which can be quantified and incorporated in IMAGE (experimental version 1.6) to arrive at the final outcomes (climate and ozone projections).

4.2 Uncertainties in climate change

Scientific uncertainties

Although scientific understanding of the climate system has been improving during the past few years, there are still many scientific uncertainties and lacunae in knowledge in this field. Such uncertainties affect our future projections of the time-scale, magnitude and regional patterns of climate change. The key areas of scientific uncertainty are (IPCC, 1990; 1992):

Sources and sinks of greenhouse gases and aerosols:

There are numerous uncertainties about the magnitude of the sources and sinks of the various greenhouse gases and aerosols and their concentrations. In the case of the main greenhouse gas, carbon dioxide (CO_2), the source associated with fossil fuel combustion is well-known (with an uncertainty of about $\pm 5\%$), but emissions associated with land use changes are poorly understood (uncertainties in order of $\pm 50\%$, IPCC (1992)). Uncertainties regarding oceanic and terrestrial sinks are in the order of $\pm 100\%$ (Rotmans, 1993). The amount of carbon remaining in the atmosphere is the only well-known component of the carbon budget. Characteristic of all of the uncertainties is the fact that the imbalance between the sources and sinks of carbon dioxide, the so-called 'missing sink', has still not yet been solved. In the case of methane (CH_4), the uncertainties regarding the magnitude of emissions from individual sources are also significant, although total global annual emissions are fairly well monitored, since they can be deduced from the magnitude of methane sinks calculated against the rate of accumulation of methane in the atmosphere. Similarly, in the case of

nitrous oxide, the sum of all presently known anthropogenic and natural sources cannot account for the higher magnitude of the observed atmospheric sink of nitrous oxide (N_2O) and other sink mechanisms, primarily stratospheric photochemical decomposition. This can only mean that either the prolificacy of some of the identified sources has been underestimated, or hitherto unidentified sources are still to be discovered.

In the case of the tropospheric ozone precursors, namely: carbon monoxide, non-methane hydrocarbons and nitrogen oxides (NO_x), there are not only uncertainties about their budgets (balances), but there also serious doubts about their trends and lifetimes. The magnitude of the sources of the halocarbons and sulphurous gases is the only sound data available.

In general, most uncertainties about sources and sinks are rooted in a lack of adequate coverage and inaccuracies in data caused by the present inadequacies in the global monitoring network which is supposed to monitor these gases.

feedback processes:

A further source of uncertainty is our deficient knowledge of the key physical and chemical processes which have a bearing on the climate system. An example of the latter is our incomplete knowledge of feedback mechanisms which may well play a major role in climate change. Such feedback processes can amplify (positive feedback) or inhibit (negative feedback) the response of the climate system to increased concentrations of greenhouse gases or radiative forcing. These feedbacks can be classified as being either biogeochemical or geophysical. Biogeochemical feedbacks influence the uptake or emissions of greenhouse gases, or affect atmospheric chemical conditions, and thereby indirectly altering the radiative characteristics of the climate system, like the CO_2 -fertilization effect. Geophysical feedback processes are caused by physical processes in the atmosphere-ocean-cryosphere system which directly modify the response to radiative forcing. Processes such as water vapour formation, cloud feedback and snow-ice albedo feedback are included in current

Table 4.1: Principal feedbacks associated with the enhanced greenhouse effect (den Elzen and Rotmans, 1993a).

Geophysical feedbacks	1)
water vapour	++
snow-ice albedo	+
clouds	?
Biogeochemical feedbacks	
carbon cycle:	
ocean temperature * 2)	+
ocean eddy diffusion *	+
ocean biology and circulation	?
oceanic gas exchange	?
vegetation albedo	+
vegetation respiration *	+
carbon dioxide fertilization *	-
soil moisture	?
redistribution of ecosystems	?
methane cycle:	
methane hydrates *	+
methane from wetlands *	+
methane from rice paddies *	+
methane from permafrost	+
tropospheric chemistry	-

1) Sign of the feedbacks:

++ = strongly amplifying global warming

+ = amplifying global warming

- = damping global warming

? = effect of feedback is unknown or uncertain

2) feedbacks marked with * are incorporated in IMAGE (experimental version 1.6)

General Circulation Models (GCMs), but almost all biogeochemical feedbacks are neglected. *Table 4.1* presents an (inexhaustive) list of both geophysical and biogeochemical feedbacks (den Elzen and Rotmans, 1993a).

clouds:

The term cloud feedback involves the effects of changes in cloud cover and in the radiative properties of cloud formation due to climate change. This feedback mechanism is currently the most significant factor of uncertainty in climate projections (magnitude of climate change). Clouds contribute to global warming by inhibiting the escape of infrared radiation from the atmosphere into space, but they also produce a cooling effect through absorption and reflection of solar radiation, and the resulting net radiative forc-

ing effect is negative. How these radiative fluxes will change under climatic disruptions is still most ambivalent due to the complexity of this feedback mechanism with its three contributory processes (IPCC, 1990), namely: cloud amount, altitude, and cloud water content (related to the optical properties). For instance, the implications of an increase of low clouds would be a cooling effect (more reflectivity), whereas an increase in high clouds depends on their altitude and coverage, and could either cause cooling or warming (IPCC, 1992). The overall sign of this feedback is not yet known. It varies from slightly negative to strongly positive in the present GCMs (Cess *et al.*, 1990). Besides global warming induced changes (cloud feedback), cloud optical properties also change as they are affected by aerosols, a change which is also highly uncertain.

Oceans:

The oceans are of importance because their thermal capacity (the exchanges of energy between the oceans and the atmosphere, between the upper layers and the deep ocean, and the transport within the ocean) and possible changes in circulation, influence the time-scale and pattern of climate change. This area is still highly uncertain.

polar ice sheets:

The response of polar ice sheets to global warming, which affects sea level rise, is also highly uncertain. IPCC (1990) concluded that it is as yet impossible to judge whether the Antarctic ice sheet as a whole is currently out of balance, and whether it is positively or negatively contributing to changes in sea level. In the future, Antarctica is expected to mitigate sea level rise due to increased snow accumulation at Antarctica associated with climate change. The possible disintegration of the West Antarctic ice sheet seems to be unlikely within the next century.

Social and economic uncertainties

The forecasting of future climate change depends on the crucial factor of future greenhouse gas emissions. In the absence of an international climate policy, emissions of

greenhouse gases are likely to increase, but the magnitude and rate of this increase are associated with a large number of social and economic uncertainties. The uncertainties arise mainly from the factors of population and economic growth, but also from technological development, agricultural activities, deforestation rates, etc. To accommodate these uncertainties, emissions scenarios are developed which represent a view of the future development of the emissions based on assumptions made of these factors. The next Chapter describes the IPCC scenarios, which are widely used by analysts in the field of climate change, in detail.

An illustration of contemporary uncertainty

As an illustration of how our knowledge of the magnitude of climate change has changed during the past decades, *Figure 4.1* charts the equilibrium global surface temperature increase due to a doubling of carbon dioxide levels (referred to as climate sensitivity) as calculated by the various GCMs and CGCMs between 1975 and 1992, as well as the range of climate sensitivity as estimated by the Climate Research Board (1979), Dickinson (1986), IPCC (1990) and IPCC (1992).

The approach to the uncertainty range in climate sensitivity adopted by Dickinson (1986) is based on considering the uncertainties in individual feedback processes (geophysical feedback processes) as determined from climate model experiments (initially GCM runs of GFDL and GISS, see *Figure 4.1*). Dickinson (1986) broadened the confidence limits of climate sensitivity arrived at by the Climate Research Board (1979) (1.5 to 4.5°C, and a central estimate of 3°C), to a range of 1.5 to 5.5°C (central estimate of 3.5°C), and a likely range (70% probability) of 2.5 to 4.5°C, whereby the probability that warming would be as low as 1°C or as dramatic as 7°C was given as 5%. The 1990 IPCC scientific assessment report (IPCC, 1990) presents the climate sensitivity results for more than twenty GCMs runs (based on almost ten GCMs) (*Figure 4.1*). The outcomes range from 1.9 to 5.2°C, with most

Figure 4.1: Increase in equilibrium global average surface air temperature due to doubling CO_2 (climate sensitivity) as calculated by GCMs and CGCMs over the period 1975 to 1992. (shaded area denotes the range of climate sensitivity as found by Climate Research Board (1979), Dickinson (1986) and IPCC (1990; 1992)).

results between 3.5 and 4.5 $^{\circ}\text{C}$, although this does not imply that the correct value for climate sensitivity is within this range since problems are inherent in modelling clouds. Generally, GCMs in which clouds are assumed to remain constant (early GCM runs of GFDL and GISS), yield results in the 2 to 3 $^{\circ}\text{C}$ range, GCMs in which cloud amount is calculated interactively from the relative humidity, but with fixed radiative properties, indicates global warming in the 4 to 5 $^{\circ}\text{C}$ range (most later GCM runs, except UKMO and CCC), and finally, GCMs (like UKMO and CCC) in which total cloud water content is modelled explicitly generate lower results (2 to 3.5 $^{\circ}\text{C}$). Using data from the latest GCM runs, IPCC (1990) estimated the range at 1.5 to 4.5 $^{\circ}\text{C}$, with a central estimate of 2.5 $^{\circ}\text{C}$ (the clustering of GCM values around 4 $^{\circ}\text{C}$ is found to be too high, because most GCMs

neglect the changes in cloud microphysics). IPCC (1990) also used Dickinson's methodology with more recent data concerning some of the individual feedbacks (water vapour feedback, and surface albedo feedback) to estimate the uncertainty range in climate sensitivity, and found a range of 1.7 to 4.1 $^{\circ}\text{C}$, with a central value of 2.4 $^{\circ}\text{C}$. Based on these findings, IPCC (1990) found it unlikely that in response to a doubling of CO_2 levels, global mean surface temperature would fall outside the range of 1.5 to 4.5 $^{\circ}\text{C}$. This range was re-affirmed in the 1992 IPCC Supplement (IPCC, 1992), with a similar best estimate of 2.5 $^{\circ}\text{C}$. IPCC (1992) summarized the results of new GCM studies, only, which in general yield similar patterns for the temperature increase resulting from a CO_2 -doubling, as presented in IPCC (1990). Although negative forcing associated with

sulphate aerosols and stratospheric ozone depletion is not implemented in the current GCMs and CGCMs, this does not affect estimate of the climate sensitivity (which is CO₂-dependent only).

In conclusion, these results tell us that over the last few decades the central estimate of the climate sensitivity has fallen from 3.5°C in the mid-eighties to 2.5°C (-30%) at present, although the uncertainty range has hardly been narrowed.

4.3 Uncertainties in stratospheric ozone depletion

Scientific uncertainties

Future global ozone losses are still surrounded by uncertainties, despite the fact that major improvements in our understanding of ozone depleting processes have been achieved during recent years, as summarized in WMO (1992). The present main uncertainties still arise from our incomplete understanding of the following two mechanisms: the local heterogeneous chemistry on the surface of stratospheric sulphate aerosols, and the transport of both ozone-depleted and chemically-perturbed polar air to middle latitudes. However, other hitherto unidentified ozone depleting processes (such as suspected non-linear mechanisms) cannot be ruled out (WMO, 1992).

Other scientific uncertainties include:

- sources of sulphate aerosols;
- photolytic cross-section and reaction rate constants for the ozone depleting compounds, although knowledge of these has been improved in the latest models based on laboratory studies;
- atmospheric lifetimes for CFCs, HCFCs, halons, and other chemicals. In particular the lifetimes of HCFCs and CH₃CCl₃ are relatively uncertain ($\pm 30\%$) (Pyle *et al.*, 1992), largely as a result of the dependency on the OH, with its complex chemistry;
- future levels of stratospheric chlorine, bromine and NO_y (from N₂O) and methane, and stratospheric temperature changes (associated with CO₂ and tropospheric ozone), and the chemical reactions involved.

Social and economic uncertainties

The production and consumption of ozone depleting substances is currently fully regulated by the Copenhagen Amendments (see Chapter 2), a document signed by most key nations, and the remaining countries have pronounced their intention to do so. However, although this is an international agreement, this is no (inter)national legislation (including punitive measures), when companies do not hold these reduction time-schedules set out in the Protocol. The latter could therefore be a major uncertainty factor in the future emissions. Another uncertainty factor is associated with the lack of emission control of the halocarbons currently stored in the various application categories, such as refrigerants. At present, only the management of the halons bank is internationally regulated.

4.4 Uncertainty analysis: methodology

Part III restricts its attention to present-day uncertainties (scientific and social uncertainties) associated with climate change, and (to a lesser extent) stratospheric ozone depletion, which can be quantitatively estimated, and incorporated in the IMAGE model. The scientific uncertainty sources are represented in the model by: (i) the model parameters: these characterize the (dynamic) behaviour of the modelled processes (e.g. diffusiveness, reaction rate, etc.); (ii) initial conditions, such as initial values for variables; (iii) the model inputs/external factors (sources and sinks); and (iv) the model structure, i.e. the form of the mathematical equations which constitute the model (Janssen *et al.*, 1990). In this approach two methodologies are used to measure and analyse the influence of uncertainty sources (i) and (ii) on the model outcome (Janssen *et al.*, 1990):

1. sensitivity analysis: the study of the influence of variations in the uncertainty sources on the model outputs. Here the uncertainty sources are varied for a range of possible values (lower till upper bound).

2. uncertainty analysis: the study of the uncertain aspects of a model, and of their influence on the model outputs. Here the uncertainty of the estimation of uncertainty sources is described by a subjective probability distribution.

In this approach, the uncertainty associated with the sources and sinks (source (iii)) are evaluated using the technique of sensitivity analysis (Chapters 6 and 7). Also the uncertainty in source (iv) is not assessed here, since at this level of modelling, many processes are modelled by parameterized representations, and therefore the uncertainty in the model structure largely corresponds to the uncertainty inherent in model parameters.

As stated above, social uncertainties are captured by emissions scenarios in the model. The uncertainty in the emissions scenarios is not evaluated here, only a range of different emissions scenarios are described (Chapter 5). An evaluation of their influence on the model outcome, merely a scenario analysis is described in the various Chapters in this section, as well as in Part IV.

Brief description of Part III

The structure of Part III is now as follows. Chapter 5 describes a wide range of IPCC emissions scenarios, as related to social uncertainties. Chapter 6 offers a model analysis of the uncertainties in the key physiological processes, for the coupled carbon cycle/climate model, i.e. the feedback pro-

cesses describing the sources and sinks in the global carbon cycle (related to the 'missing sink' discussion). It is shown here that variations in the model parameters representing these processes strongly influence the balancing of the past and present carbon budget, and can thus result in a wide range of different future atmospheric CO₂ concentration projections. Chapter 7 presents a model and scenario analysis of the main gases in the CH₄-CO-OH cycle, methane, carbon monoxide, non-methane hydrocarbons, halocarbons and NO_x, which all influence the sources and sinks of methane (the second most important greenhouse gas). This analysis is based on simulation experiments with the methane model (part of the atmospheric chemistry model). Chapter 8 describes an uncertainty and sensitivity analysis of the carbon cycle model and the halocarbon model, with as model outcomes, the projected atmospheric concentration of CO₂, and the atmospheric concentration of CFC-11, CFC-12 and chlorine, respectively. It also presents an uncertainty and sensitivity analysis for the entire integrated modelling framework IMAGE (experimental version 1.6), based on two model outcomes, namely: radiative forcing and global average surface temperature increase. To estimate the contribution of the individual model parameters to the total uncertainty in the different model outcomes, the mathematical technique of metamodelling, or linear regression and correlation analysis, is used.

5 IPCC scenarios

5.1 Introduction

A wide range of human activities results in the emission of greenhouse gases. The sources of anthropogenic emissions can be categorized as follows: energy production and use, non-energy producing industrial activities (primarily the production of CFCs), deforestation, agricultural activities, and other emission sources (landfills, cement factories, etc.) (IPCC, 1991b). Given the current lack of an international climate policy, the emissions of greenhouse gases from most sources (except the currently regulated halocarbons) is likely to further increase in future as a result of ongoing increases in population and economic growth. Over and above these two key factors, there are also others which will influence future emissions, such as technological developments, the economic costs of technology used to convert energy from one form to another, end-use efficiency, deforestation rates, agricultural emissions, etc. The probable future developments in these factors are obscured by significant uncertainties ('social and economic uncertainties'). In order to accommodate these uncertainties, emission scenarios are developed which represent alternative views of the future on the basis of assumptions regarding: population and economic growth, agricultural and technological developments. These scenarios should not be seen as predictions, rather as possible directions in which future emissions may evolve in the absence, or inadequacy, of greenhouse gas reduction efforts.

This Chapter briefly describes the four IPCC-1990 scenarios (section 5.2), generated by the IPCC Working group III (IPCC, 1991b), which have been widely used by scientists (e.g. as inputs for climate models) in the field of climate change, and are also

employed in all of the analyses presented here. These scenarios represent a broad range of possible policies which would limit the emissions of greenhouse gases (IPCC, 1991b).

In 1992, Leggett *et al.* (1992) used new information to update: the 'no climate policy' scenario, the IPCC-1990 Business-as-Usual (BaU90) scenario, a set of six emission scenarios, and the IPCC-1992 scenarios (IS92a-f scenarios). Section 5.3 briefly reviews these scenarios, which are evaluated in Chapter 11.

5.2 IPCC-1990 scenarios

5.2.1 Introduction

In 1989, the IPCC's Working Group III requested the formation of a US-Netherlands expert group to develop a set of scenarios pertaining to global emissions of CO₂, CH₄, N₂O, 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 at EPA), and IMAGE (developed at RIVM). The ASF model is a framework consisting of emission models relevant to various sectors: energy, industry, agriculture, forests and land conversion, as well as a number of sectors which are minor sources. Each emission model combines assumptions concerning population growth, economic growth, technological developments, structural change, resource availability and emission coefficients to estimate future emissions (EPA, 1989). The expert group published a set of four emission scenarios, each representing a different view of future global climate change and presented them towards the end of 1989 (Expert group on

emissions scenarios, 1990a; 1990b [1]; IPCC, 1991b; Swart *et al.*, 1990).

5.2.2 Methodology

For the development of these four scenarios, the expert group used the concept of CO₂-equivalent concentration, defined as the concentration of CO₂ that by itself, would produce the increase in direct radiative forcing generated by all of the greenhouse gases involved. Three scenarios were designed in such a way that they envisaged a doubling of the CO₂-equivalent concentration in the years 2030, 2060, and subsequently in 2090, and were named, respectively the Business-as-Usual (BaU90) scenario, the Low Emissions (Low90) scenario and the Control Policies (CP90) scenario. In addition, the expert group was asked to develop an additional fourth scenario that would lead to stabilization of the CO₂-equivalent concentration at a level well below a doubling of pre-industrial atmospheric CO₂. EPA devoted a great deal of attention to present assessments of the feasibility of the scenario, primarily with respect to the technical options, and developed the Accelerated Policies (AP90) scenario. This scenario assumes that economic, political, and technological constraints would preclude reductions in emissions in the short term, and envisages the CO₂-emissions increasing slightly over the next decades, and being reduced drastically after 2025. In addition, the RIVM developed an alternative case (the Alternative Accelerated Policies scenario), which reflects the need to slow down climate change as soon as possible. Consequently, it was assumed that reductions in CO₂-emissions could be realized earlier (Elzen *et al.*, 1990a; Swart *et al.*, 1990).

It is evident that for each scenario, there are several equally-plausible paths which would arrive at the CO₂-equivalent doubling level. The methodology used by the expert

group to create these four scenarios involved two steps. Firstly, for each of the four emission scenarios (all scenarios except the Alternative Accelerated Policies scenario) the group designed two detailed scenarios. In the construction of these eight scenarios, several key variables influencing 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, were varied to obtain the CO₂-equivalent concentration target (IPCC, 1991b). An important variable was future economic growth, with a higher and lower economic growth rate for each scenario.

In the second step, the two detailed (lower and higher economic growth) scenarios are combined to create an averaged scenario. For all four scenarios in the high economic growth case, the average annual rate of GNP growth for the world decreases from 3.6% over the period 1985 to 2000, to about 2.6% per annum between 2025 and 2100, while in the case of lower economic growth the fall is from 2.2% p.a. (1985-2000) to 1.3% (2025-2100). Another main parameter which is the same in all four scenarios is future population growth and is based on World Bank data (Zachariah and Vu, 1988). Global population reaches 9.5 billion by 2050 and 10.4 billion by 2100 with most of the growth in the developing world. Other key variables that have not been altered for any of the scenarios are the index year (1985) emissions for each greenhouse gas.

5.2.3 Description of the IPCC-1990 scenarios

The detailed backgrounds, and the assumptions underpinning the scenario-dependent key parameters for the four scenarios are tabulated in Table 5.1. In this section, the IPCC-1990 scenarios and Alternative Accelerated Policies scenario will be described briefly. The Business-as-Usual scenario assumes that few or no steps are taken to limit greenhouse gas emissions. Energy use and clearing of tropical rainforests continue to increase, and

[1] Part II of Appendix 'Emissions scenarios' by Expert group on emission scenarios (1990b) was prepared by the Dutch: Elzen, M.G.J. den, Swart, R.J., and Rotmans, J. (1990a), for the Response Strategies Working Group (Working Group III) of the IPCC (here referred to as Elzen *et al.* (1990a)).

Table 5.1a : Description of the IPCC-1990 scenarios for CO₂ and CH₄ (IPCC, 1991b).

scenario	Business-As-Usual	Low Emissions	Control Policies	Accelerated. Policies
gas: CO ₂	BaU90	Low90	CP90	AP90
Energy	<p>Increase in energy use, mainly by use of fossil fuels (coal) by higher economic growth. Primary energy supply increases to 565 EJ by 2025 (1.7%/yr) and to 1205 EJ by 2100 (0.95%/yr).</p> <p>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.</p>	<p>Primary energy supply reaches 412 EJ in 2025 and to 640 EJ in 2100, mainly because of the improvements in energy efficiency.</p> <p>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.</p>	<p>Primary energy same as Low90. Non-fossil fuel energy supplies start to play a larger role after 2025, covering 71% of primary energy by 2100.</p> <p>The share of primary energy provided by fossil fuels decline after 2050, while the non-fossil fuels increase thereafter.</p>	<p>Same as CP90, except that the energy use is slightly higher in the mid-century by increased availability of biomass supplies and their lower costs.</p> <p>The share of primary energy provided by non-fossil sources increases to 41% in 2025, to 79% by 2100.</p>
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%.	Same as Low90.	Same as Low90.
Emission	CO ₂ -emissions due to commercial energy and cement reaches 22.0 GtC/yr in 2100 (360% of 1990 level).	CO ₂ emissions due to commercial energy and cement increase (+4.5 GtC/yr, or 75% by 2100).	CO ₂ emissions increase till 2050 to 7.1 GtC/yr, and thereafter decreases to 3.5 GtC/yr (60% of 1990 level).	CO ₂ emissions decrease in the energy sector (-3.0 GtC/yr or -50% in 2100).
Deforestation	Deforestation rate is the averaged rate of to 15 Mha/yr in 2100 (moderate case) and of to 34 Mha/yr in 2050 and complete deforestation by 2075 (rapid case).	Reforestation case; deforestation stops in 2025, and about 1000 million ha are reforested in 2100.	Same as Low90.	Same as Low90.
gas: CH ₄	BaU90	Low90	CP90	AP90
Energy	Major increase in CH ₄ emissions due to increase in energy production of coal and gas (+300% in 2100).	CH ₄ emissions from energy consumption grow with increasing consumption till 75% of 1990 level in 2100.	CH ₄ emissions from energy consumption increase (+46% in 2050), and thereafter decrease due to decreasing energy consumption till 75% of 1990 level in 2100.	CH ₄ emissions from energy consumption increase (+15% in 2000), decrease thereafter due to decreasing energy consumption till +65% level in 2100.
Landfills	CH ₄ emissions from waste disposal grow with population and economy (+350% in 2100).	CH ₄ emissions from landfills grow till 2050, and then decline by control technologies till +13% of 1990 level).	CH ₄ emissions from landfills grow till 2050, and then start to decline by control technologies till +13% of 1990 level in 2100.	Same as CP90
Rice	CH ₄ emissions from rice paddies grow with the area harvested (+45% in 2100).	Same as BaU90	CH ₄ emissions from rice paddies decrease after 2050 by altering rice cultivar practices to 80% of 1990 level.	Same as CP90
Enteric fermentation	CH ₄ emissions from cattle grow with an increasing livestock population (+125% in 2100)	Same as BaU90	CH ₄ emissions from cattle grow controlled by adopting meat and dairy production techniques, till +30% in 2100.	Same as CP90

Table 5.1b: Description of the IPCC-1990 scenarios for CO, N₂O and halocarbons (IPCC, 1991b).

scenario	Business-As-Usual	Low Emissions	Control Policies	Accelerated Policies
gas: CO	BaU90	Low90	CP90	AP90
Energy	CO emissions by energy consumption grow with increasing transportation and other energy consumption (+245% in 2100).	CO emissions from energy consumption and transport decrease by 1990 control technologies on mobile and stationary sources (-60% in 2100).	Same as Low90	Same as Low90
Deforestation	CO emissions from deforestation grow with increasing rates of forest destruction to +90% in 2025, then decrease by forest depletion.	CO emissions from deforestation decrease with decreasing rates of deforestation (-100% in 2100).	Same as Low90	Same as Low90
gas: N ₂ O	BaU90	Low90	CP90	AP90
Energy	Increase in N ₂ O emissions from coal use (3.1 Tg/yr or 280% in 2100).	Increase in N ₂ O emissions related to energy use (0.7 Tg/yr or 64% in 2100).	Increasing N ₂ O emissions till 2050 to 1.4 Tg/yr, thereafter a decrease till 1990 level.	Increasing N ₂ O emissions till 2050 to 1.2 Tg/yr, thereafter a decrease till 1990 level.
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). or +38% in 2100).	N ₂ O 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 ₂ O 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 ₂ O emissions from biomass burning increase till 2050 with 40%, thereafter decrease till 90% of 1990 level.	N ₂ O emissions from biomass burning decrease (-0.5 Tg/yr or -35% in 2100).	Same as Low90	Same as Low90
Halocarbons:	BaU90	Low90	CP90	AP90
CFCs, 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.	Complete phase out of CFCs by the year 2000 and for methyl chloroform and carbon tetrachloride 10 years later.	Same as Low90.
HCFCs and HFCs	Alternatives, HCFCs and HFCs replace 35% of the phased-out CFCs and grow with 2.5% annually.	Same as BaU90	Same as BaU90	Same as BaU90

fossil fuels, in particular coal, remain the world's primary energy sources. The emissions of the greenhouse gases, CO₂, CH₄ and N₂O increase continuously, and the CO₂-emissions in particular are doubled within forty years. The Montreal Protocol is not

strengthened and participation of the developing countries is assumed to be only 85%. The emissions of CFCs decline and stabilize below present levels, but the emissions of the alternatives, i.e. HCFC-22 increase continuously. The Low Emissions scenario assumes

that environmental concerns result in steps aimed at reducing the growth of greenhouse gas emissions; energy efficiency measures are implemented, the proportion of the world's primary energy provided by natural gas increases; there is full compliance with the Montreal Protocol and tropical deforestation is halted and reversed. CO₂ emissions do not double before 2100. The Control Policies scenario envisages a world in which concern for climate change and other environmental issues results in steps being taken over and above those envisaged in the Low emissions scenario. Technological development, and governmental efforts result in the rapid penetration of renewable resources in the latter half of the next century. The reinforced Montreal Protocol involves the phasing-out of CFCs by the year 2000. As a result of new agricultural policies, emissions of CO₂, CH₄ and N₂O start to decline in the middle of the next century. The Accelerated Policies scenario differs from the Control Policies scenario in that in the former the development and market penetration of renewable energy sources and nuclear energy is encouraged. This results in a decline in fossil fuel CO₂ emissions after 2000, while fossil fuel related levels by 2100 are half of what they were in 1985. In these scenarios, deforestation is assumed to have stopped by the turn of the century and a net increase through large-scale reforestation pro-

grammes is envisaged. Insofar as other greenhouse gases are concerned, the assumptions are largely identical to those adopted in the Control Policies scenario.

In the Alternative Accelerated Policies scenario, CO₂ emissions are assumed to start their decline immediately (Elzen *et al.*, 1990a). In theory, this scenario could be achieved technologically and would allow for a more gradual shift to a low-CO₂ energy system. The low CO₂-emissions are primarily to be achieved via energy efficiency improvements and decreasing prices of renewable sources of energy as a result of intensified research and development (notably solar energy). To implement a change from the premises of the present trend (BaU90 scenario) to the Alternative Accelerated Policies scenario, an average improvement in energy efficiency of 1 to 2% annually will be required in the developing countries and 2 to 3.5% in the industrialized countries (RIVM, 1991). Furthermore, a reduction of the carbon intensity of the fuel supply by more than 1.5 to 2% per year will be needed. This scenario demonstrates that it is possible to allow emissions from the developing countries to increase for some time if the industrialized countries set an example by stabilizing them from now on and reducing them by the next century.

The emissions of the greenhouse gases for all scenarios are given in Table 5.2. Finally,

Figure 5.1: CO₂ emissions from fossil fuel combustion and cement manufacturing for the four IPCC-1990 scenarios (IPCC, 1991b).

Figure 5.1 depicts the projected CO₂-emissions. Table 5.3 lists some of the key characteristics of the scenarios.

5.3 IPCC-1992 scenarios

5.3.1 Introduction

In 1992, a new set of six updated emission scenarios for the greenhouse gases (CO₂, CH₄, N₂O, halocarbons), the tropospheric ozone precursors (NO_x, CO), volatile organic compounds (VOCs), and sulphur oxides (SO_x) based on the IPCC-1990 Business-as-Usual scenario was produced by the IPCC (Pepper *et al.*, 1992; Leggett *et al.*, 1992). These scenarios differ fundamentally from the previous IPCC scenarios in a number of aspects. In the first place, these scenarios take account of on events which have occurred, and new information which has appeared, since the development of the original IPCC scenarios. This information reflects: the London Amendments to the Montreal Protocol; a recent analysis of population forecasts by the World Bank (1991) and the UN (1990; 1992); a new greenhouse gas scenario for the period up to 2025 from the IPCC Energy and Industry Sub-Group (EIS); political events and economic changes in the COS, Eastern Europe and the Middle East; and improved understanding of the current sources and sinks of greenhouse gases. The total emissions of CH₄ have not changed significantly since the BaU90 estimate. Some sources have lowered their emission levels (rice, biomass burning) while other sources have increased them (landfills, energy). Total emissions of N₂O are similar to those estimated in the BaU90 assessment, although the subdivision of the individual sources is somewhat different (cultivated soils and industry are more important than fuel combustion). The emissions of the other greenhouse gases have now been updated. CO₂ emissions from deforestation have increased significant, as a result of higher rates of tropical deforestation, according to recent FAO (1991) estimates, and new data on forest biomass gathered by the OECD (1991). Secondly these scenarios are,

methodologically speaking, more soundly constructed than the earlier IPCC scenarios, since the new versions were not developed 'top-down' to achieve a specific goal (timing of the doubling of the CO₂-equivalent concentration) as in the original IPCC-1990 scenarios, but instead were based on a wide range of assumptions regarding demographic, socio-economic, and technological factors which influence emissions in the absence of coordinated policy response to climate change (Pepper *et al.*, 1992; Leggett *et al.*, 1992).

5.3.2 Methodology

The six IPCC scenarios, which are known as the IPCC-1992 scenarios (IS92 a-f), consider a wide range of possible future emissions. In the analysis of Leggett *et al.* (1992), the ASF model has been used as a primary tool for integrating the assumptions and calculating the future emissions of the greenhouse gases.

The IPCC-1992 scenarios IS92a and IS92b most resemble straightforward updates of the BaU90 scenario. In order to address the significant uncertainties inherent in future patterns of human activity, such as demographic, economic and technological developments, four additional scenarios were created using modified key parameters. Generally-speaking, the six scenarios differ from each other in their assumptions about the various key factors: population growth, economic growth, structural changes in economies (*viz.* the COS, and Eastern Europe), energy prices, technological developments, fossil fuel supplies, nuclear and renewable energy production capacity, existing or future international emission control agreements, and agricultural activities.

The main key parameters which significantly determine the emissions of greenhouse gases are the population and economic growth assumptions. Since the development of the original IPCC-1990 scenarios, the assumed population and economic growth rates have increased. The forecast of future population for the BaU90 scenario was made by the World Bank (Zachariah and Vu, 1988), and subsequently updated (World Bank, 1991). The updated population growth

Table 5.2 : Greenhouse Gas Emissions (IPCC, 1991b) (2)

Business-as-Usual scenario	1985	2000	2025	2050	2075	2100
CO ₂ Fossil fuel burning (GtC/yr)	5.2	6.7	10.1	13.8	18.0	22.0
CO ₂ Deforestation (GtC/yr)	0.7	1.0	1.4	1.4	0.7	0.4
N ₂ O (TgN/yr)	12.5	14.2	16.4	17.3	17.3	17.6
CH ₄ (Tg/yr)	541	614	761	899	992	1063
NO _x (TgN/yr)	51	56	68	81	91	102
CO (TgC/yr)	541	616	781	882	839	928
CFC-11 (Gg/yr)	278	305	245	252	253	253
CFC-12 (Gg/yr)	362	376	303	314	316	316
HCFC-22 (Gg/yr)	97	523	1340	2681	2961	2961
Low Emissions scenario	1985	2000	2025	2050	2075	2100
CO ₂ Fossil fuel burning (GtC/yr)	5.2	5.8	6.8	7.8	8.9	10.5
CO ₂ Deforestation (GtC/yr)	0.7	-0.2	-0.5	-0.3	-0.2	-0.2
N ₂ O (TgN/yr)	12.5	13.1	13.9	14.1	14.3	14.6
CH ₄ (Tg/yr)	541	577	665	724	732	736
NO _x (TgN/yr)	51	50	46	41	41	44
CO (TgC/yr)	541	428	336	285	280	281
CFC-11 (Gg/yr)	278	302	227	223	223	223
CFC-12 (Gg/yr)	362	372	279	278	278	278
HCFC-22 (Gg/yr)	97	526	1357	2707	2988	2988
Control Policies scenario	1985	2000	2025	2050	2075	2100
CO ₂ Fossil fuel burning (GtC/yr)	5.2	5.8	6.7	7.4	5.2	3.7
CO ₂ Deforestation (GtC/yr)	0.7	-0.2	-0.5	-0.3	-0.2	-0.2
N ₂ O (TgN/yr)	12.5	12.9	13.2	13.0	12.5	12.2
CH ₄ (Tg/yr)	541	558	608	622	562	505
NO _x (TgN/yr)	51	50	46	42	39	39
CO (TgC/yr)	541	427	336	285	274	270
CFC-11 (Gg/yr)	278	197	11	0	0	0
CFC-12 (Gg/yr)	362	262	10	0	0	0
HCFC-22 (Gg/yr)	97	639	1572	2927	3209	3209
Accelerated Policies scenario	1985	2000	2025	2050	2075	2100
CO ₂ Fossil fuel burning (GtC/yr)	5.2	5.9	5.6	3.2	3.1	2.9
CO ₂ Deforestation (GtC/yr)	0.7	-0.2	-0.5	-0.3	-0.2	-0.2
N ₂ O (TgN/yr)	12.5	12.9	13.1	12.7	12.5	12.3
CH ₄ (Tg/yr)	541	566	584	553	530	502
NO _x (TgN/yr)	51	51	50	44	43	42
CO (TgC/yr)	541	411	341	287	285	281
CFC-11 (Gg/yr)	278	197	11	0	0	0
CFC-12 (Gg/yr)	362	262	10	0	0	0
HCFC-22 (Gg/yr)	97	639	1572	2927	3209	3209
Alternative Accelerated Policies scenario	1985	2000	2025	2050	2075	2100
CO ₂ Fossil fuel burning (GtC/yr)	5.2	4.9	4.3	4.0	3.6	2.8
CO ₂ Deforestation (GtC/yr)	0.7	-0.2	-0.5	-0.3	-0.2	-0.2

[2] The incorporation of these emissions scenarios in the IMAGE model poses some minor problems with the starting (1985) emissions of the scenarios and the estimates for the 1990 emissions of IPCC (1990; 1992) as included in the model. The 1990 emissions of IPCC (1990) are equal to: fossil-fuel CO₂, 6.0 GtC/yr; Cement CO₂, 0.2 GtC/yr; Land-use CO₂, 1.3 GtC/yr; CH₄, 506 TgCH₄/yr; N₂O, 12.9 TgN/yr; CFCs, 827 kt/yr; HCFCs, 143 kt/yr; and HFCs, 0 kt/yr. Firstly, the CO₂-emissions from fossil fuel use and cement manufacturing for the Low Emissions and Control Policies scenarios for the year 2000 are too low in the original scenarios compared with the 1990 emissions of IPCC (1990). Here, the CO₂-emissions are linearly interpolated between 1990 and 2025. Secondly, CO₂-emissions from deforestation for all scenarios are too low, about 0.8 GtC in 1990, whereas present emissions are estimated at 1.6 GtC (IPCC, 1990). This discrepancy is solved since IMAGE (experimental version 1.6) generates its own CO₂ emissions from deforestation, which were already higher than the IPCC 1990 estimates.

Table 5.3: Key characteristics of the IPCC-scenarios (IPCC, 1991b)

scenario	Business-As-Usual scenario	Low Emissions scenario	Control Policies scenario	Accelerated Policies scenario
Energy	Coal-intensive	Natural Gas-intensive	Non-Fossil intensive	Early Non-Fossil intensive
Energy Demand	Moderate Efficiency	High Efficiency	High Efficiency	High Efficiency
Control Technology	Modest Controls	Stringent Controls	Stringent Controls	Stringent Controls
CFCs	Protocol/Low Compliance	Protocol/Full Compliance	Phase Out	Phase Out
Deforestation	Moderate	Reforestation	Reforestation	Reforestation
Agriculture	Current Factors	Current Factors	Declining Factors	Declining Factors

prediction is nearly 10% higher than the rate assumed for the original IPCC assessment: global population is expected to increase from 4.84 billion in 1985, to 8.4 billion in 2025, and to 11.3 billion in 2100, mainly as a result of growth in the developing countries. The UN has also updated its population forecasts (UN Population Division, 1992), whereby the population assumptions in the UN medium case reach 8.51 billion in 2025, and 11.2 billion in 2100 (both projections being 1% lower than the World Bank estimate). The UN medium-low and medium-high cases reach 6.4 billion and 17.6 billion, respectively, in 2100.

5.3.3 Description of the IPCC-1992 scenarios

Table 5.4 (equivalent to Table A3.1 in Leggett *et al.* (1992) summarizes the various assumptions associated with the key factors for the six scenarios, which are discussed in detail in Pepper *et al.* (1992), and summarized in Leggett *et al.* (1992).

The IS92a and IS92b scenarios adopt the World Bank (1991) population forecast as their assumption. The economic growth assumptions as adopted in the IS92a and IS92b scenarios are higher than those used in the BaU90 scenario, especially with regard

to Africa, China and Southeast Asia (see Table 5.4). The global energy intensity (energy per unit of GNP) in scenarios IS92a and IS92b decreases globally at an annual rate of 0.8% until 2025, and at 1.0% annually from 2025 to 2100, substantial structural changes being anticipated in China up to 2100, and Eastern Europe and the COS in the period 1990 to 2025. Notwithstanding such decreases in energy intensity, the global commercial primary energy use rises steadily up to 2100, as a result of increases in population and income, from 344 exajoules (EJ) in 1990, to 708 EJ by 2025 and to 1453 EJ by 2100 [3]. The contributions of various sources of energy are expected to change due to assumed limitations in fossil-fuel reserves, and expected advances in energy technologies, as well as calculated increases in energy prices, and decreasing costs of non-energy supplies. As a result, conventional oil and gas expected to be gradually replaced by unconventional fossil sources, synthetic fuels from coal, and non-fossil energy supplies, the fossil share representing over 85% up to 2025, when it starts to decline to 57% by

[3] Primary energy use in the BaU90 scenario was predicted as 473 to 657 EJ in 2025 and 782 to 1682 EJ in 2100, the range representing the low and high economic case.

Table 5.4: Summary of assumptions in the six IPCC-1992 scenarios (Table A3.1 in Leggett et al., 1992)

Scenario	Population	Economic growth	Energy Supply	Other	halocarbons
IS92a	World Bank 1991 11.3 billion by 2100	1990-2025: 2.9% 1990-2100: 2.3%	12,000 EJ in Conventional Oil 13,000 EJ Natural Gas Solar costs fall to \$0.075/kWh 191 EJ of biofuels available at \$70/barrel	Legally enacted and internationally agreed controls on SO _x , NO _x , and NMVOC emissions. Efforts to reduce emissions of SO _x , NO _x and CO in developing countries by middle of next century.	Partial compliance with London Amendments. Technological transfer results in gradual phase out of CFCs in non-signatory countries by 2075.
IS92b	World Bank 1991 11.3 billion by 2100	1990-2025: 2.9% 1990-2100: 2.3%	Same as IS92a	Same as IS92a plus commitments by many OECD countries to stabilize or reduce CO ₂ emissions.	Global compliance with scheduled phase out of London Amendments.
IS92c	UN Medium Low Case 6.4 billion by 2100	1990-2025: 2.0% 1990-2100: 1.2%	8,000 EJ Conventional Oil 7,300 EJ Natural Gas Nuclear costs decline by 0.4% annually	Same as IS92a	Same as IS92a
IS92d	UN Medium Low Case 6.4 billion by 2100	1990-2025: 2.7% 1990-2100: 2.0%	Oil and gas same as IS92c Solar costs fall to \$0.065/kWh 272 EJ of biofuels available at \$50/barrel	Emission controls extended worldwide for CO, NO _x , NMVOC and SO _x . Halt deforestation. Capture and use of emissions from coal mining and gas production and use.	CFC production phase out by 1997 for industrialized countries. Phase out of HCFCs.
IS92e	World Bank 1991 11.3 billion by 2100	1990-2025: 3.5% 1990-2100: 3.0%	18,400 EJ conventional oil Gas same as IS92a Phase out nuclear by 2075	Emission controls which increase fossil energy costs by 30%.	Same as IS92d.
IS92f	UN High nCase 17.6 billion by 2100	1990-2025: 2.9% 1990-2100: 2.3%	Oil and gas same as IS92c Solar costs fall to \$0.083/kWh Nuclear costs increase to \$0.09/kWh	Same as IS92a	Same as IS92a.

2100 (despite the almost threefold increase in energy consumption). CO₂ emissions associated with energy use as adopted in the IS92a scenario increase from 6.0 GtC in 1990 to 10.7 GtC in 2025 and 19.8 GtC in 2100. In comparison with the BaU90 scenario, this scenario envisages a somewhat faster growth before 2025, and a more moderate growth afterwards. The higher CO₂ emissions until 2025 are caused by higher population and economic growth, and a slower penetration of energy efficiency improvements. After 2025, the contribution of non-fossil fuels to energy supplies in the IS92a scenario is more optimistic, i.e. smaller, than in the original BaU90 scenario. The IS92b scenario incorporates the goal of stabilization of fossil CO₂ emissions by the year 2000, as proposed by most of the OECD countries, and assumes that most of the OECD countries, achieve this goal, and stabilize their emissions by 2000, while the rest of the world does not adopt similar measures. This policy implies an 11% reduction in CO₂ emissions from the OECD countries vis-à-vis the emissions envisaged in the IS92a scenario, but no more than a 4% reduction of global emissions.

In the IS92a and IS92b scenarios, tropical forest clearing increases from 17 million hectares (Mha) per annum over the period 1981 to 1990 (FAO, 1991), to 20 Mha/annum by 2025, an increase due to growth in population. It then declines to 2.2 Mha/annum by 2100. Both scenario have also incorporated legally-enacted and internationally-agreed emission controls, such as the London Amendments, the amended US Clean Air Act, and the SO_x, NO_x and VOC Protocols, although the IS92a scenario assumes only a partial compliance with the London Amendments, together with a phase-out by 2025 for the non-signatory countries.

In the other four additional scenarios, the sensitivity of future greenhouse gas emissions to a wider range of assumptions for the key variables is examined. In the IS92c scenario (the lowest scenario) the UN medium-low population forecast (UN, 1992) is implemented, which assumes a decline of the population in the 21st century. This scenario also assumes a lower growth in GDP per

capita, and low oil and gas resource availability, resulting in higher fossil fuel prices and thus an expansion of the role of nuclear and renewable energy sources. Deforestation is slowed down by lower population growth. Moreover, the same emission control policies as those assumed in IS92a are implemented. The IS92d scenario also employs the UN's low population forecast, but is more optimistic vis-à-vis IS92c about economic growth and environmental protection policy, including actions that could be taken as a result of public concern about local or regional air pollution, waste disposal, deforestation, stratospheric ozone depletion, etc. As in IS92c, a lack of oil and gas availability means that renewable and nuclear energy sources replace fossil fuels. The highest scenario, i.e. IS92e, combines the moderate population growth predicted by the World Bank (1991), with high economic growth, high fossil fuel availability, and a phase-out of nuclear power by 2075, but also allows for a 30% environmental surcharge on fossil energy use. The CFC-policy is the same as in IS92d, while deforestation is the same as in IS92a and IS92b. The IS92f estimates are more pessimistic than those in IS92e, since the former scenario assumes the high UN population growth forecasts, together with the same economic growth and environmental restrictions which are assumed in IS92a. It also assumes a high fossil fuel availability, increasing costs of nuclear power, and less improvement in renewable energy technologies and cost-savings.

Table 5.5 summarizes the emissions of all greenhouse gases for the six IPCC-1992 scenarios. Figure 5.2 shows the CO₂-emissions associated with energy use and cement production for these scenarios.

5.4 Conclusions

In order to take account of the many social and economic uncertainties associated with greenhouse gas emissions, such as population, economic growth, structural changes in economies (such as the COS, and Eastern Europe), energy prices, technological developments, fossil fuel supplies, nuclear and

Table 5.5 : Greenhouse Gas Emissions for the six IPCC-1992 scenarios (Pepper et al., 1992)

scenario	Year	CO ₂ (ind) (GtC)	CO ₂ (def) (GtC)	CH ₄ (Tg)	N ₂ O (Tg)	CFCs (Gg)	HCFCs (Gg)	HFCs (Gg)	Other halocarbons (Gg)	SO _x (TgS)
IS92a	1990	6.2	1.3	506	12.9	827	143	0	864	98
	2025	11.1	1.1	659	15.8	217	824	511	121	141
	2100	20.4	-0.1	917	17.0	3	1074	1823	0	169
IS92b	2025	10.7	1.1	659	15.7	36	847	533	3	140
	2100	19.2	-0.1	917	16.9	0	1075	1823	0	164
IS92c	2025	7.7	1.3	589	15.0	217	824	511	121	115
	2100	4.8	-0.2	546	13.7	3	1074	1823	0	87
IS92d	2025	9.0	0.3	584	15.1	24	316	1064	3	104
	2100	10.4	-0.1	567	14.5	0	0	2764	0	87
IS92e	2025	13.8	1.1	692	16.3	24	316	1064	3	163
	2100	35.9	-0.1	1072	19.1	0	0	2764	0	254
IS92f	2025	13.0	1.3	697	16.2	217	824	511	121	151
	2100	26.6	0.0	1168	19.0	3	1074	1823	0	204

renewable energy source availability, existing or future international emission control agreements, and agricultural activities, emission scenarios are developed which represent a view of the future on the basis of assumptions regarding these key variables. These

scenarios should not be seen as predictions of the future, but rather as a possible future direction in which future emissions may evolve in the absence of greenhouse gas reduction efforts.

This Chapter has briefly discussed the

Figure 5.2: CO₂ emissions from fossil fuel combustion and cement manufacturing for the IPCC-1992 scenarios (Pepper et al., 1992).

original IPCC-1990 scenarios and the new set of IPCC-1992 scenarios. As stated in our introduction, (section 5.2.1), the IPCC-1992 scenarios differ from the original scenarios in various aspects. Firstly, these scenarios are based on events and new information after the development of the IPCC-1990 scenarios. Secondly, these scenarios are constructed in a methodologically sounder fashion than the earlier IPCC scenarios, since they were not developed 'top-down' to achieve a specific goal (timing of the doubling of the CO₂-equivalent concentration) as in the original 1990 scenarios, but were rather based on a wide range of assumptions

regarding the key variables as described above.

The IS92a and IS92b scenarios update the original BaU90 scenario, because of the fact that these are based on similar assumptions for the key variables as were adopted for the BaU90. These scenarios envisage a range of 10.3 to 10.7 GtC in 2025, and 18.6 to 19.8 GtC in 2100. However, the other four IPCC-1992 scenarios, incorporating a broader range of plausible assumptions than that underpinning the BaU90, IS92a, and IS92b, envisage a much wider range of CO₂ emissions, from 7 to 14 GtC in 2025, and 5 to 35 GtC in 2100.

6

Could terrestrial feedbacks explain the 'missing' carbon sink?

This Chapter is based on: Rotmans, J., and Elzen, M.G.J. den (1993a): Modelling feedback mechanisms in the carbon cycle. Tellus 45B.

6.1 Introduction

Within the carbon cycle there is an inadequate understanding of the many potential feedbacks such as the response to increasing atmospheric carbon dioxide (CO_2) and rising temperature. These feedback processes belong to the group of biogeochemical feedbacks, which influence the uptake or emission of greenhouse gases and thereby indirectly altering the radiative characteristics of the climate system. The other group of feedback processes can be classified as geophysical feedbacks, which are caused by physical processes in the atmosphere-ocean-cryosphere system and directly affect the response to the radiative forcing. In general, feedback processes can amplify (positive feedback) or damp (negative feedback) the response of the climate system resulting from increased concentrations or radiative forcing. This Chapter primarily focusses on the role of biogeochemical feedbacks within the carbon cycle.

In order to match modelled and observed atmospheric CO_2 -concentrations, carbon cycle models can be used in two different ways. The methodology which is usually applied is running a carbon cycle model in an inverse mode and deriving net biospheric emissions (inverse modelling), i.e. emissions due to land use changes (mainly deforestation), and other unspecified sources and/or sinks. Examples of this approach can be found in Siegenthaler and Oeschger (1987), Enting and Pearman (1987) and Wigley (1991). An important characteristic of those inverse models is that if the net biospheric emissions do not match with current ecological estimates for deforestation and land use

changes, then other sinks are introduced in order to balance the global carbon budget. An alternative approach is to run a carbon cycle model in a forward mode, and test a biospheric source hypothesis (forward modelling). For instance Goudriaan and Ketner (1984) have done this. Here the coupled carbon cycle/climate model of IMAGE (experimental version 1.6) is used to balance the global carbon budget. The carbon cycle model is an extended version of that of Goudriaan and Ketner, including a land use model as described in Rotmans and Swart (1991).

This method is not new, because others have done this before. Harvey (1989a) and Wigley (1992) have attempted to balance the carbon budget by changing the CO_2 fertilization feedback and the ocean CO_2 flux. Wigley (1992) has used an inverse carbon cycle model in which he changed the CO_2 fertilization feedback and ocean CO_2 flux in order to balance the carbon budget and also make future CO_2 projections. In this Chapter a forward modelling approach is used, which additionally includes temperature related feedback terms in order to balance the past and present global carbon budget. After generally discussing the carbon balance concept (section 6.2), section 6.3 describes the coupled carbon cycle/climate model, followed by a description of how some of the terrestrial feedbacks are incorporated and used in the model. Then section 6.4 presents a series of simulation experiments with the model. Finally, the results of a sensitivity analysis are presented and the results are evaluated.

6.2 The carbon balance concept

The natural global carbon cycle encompasses exchanges of CO₂ between 3 reservoirs of CO₂, the atmosphere, the oceans and the terrestrial biosphere, of tens of billions tons of carbon a year. The extra man-made addition through the burning of fossil fuels and changing land use is relatively small compared with some of these fluxes. However, there is strong evidence to indicate that man-made addition of carbon is the cause for upsetting the balance of the carbon cycle leading to an increase in the atmospheric CO₂ concentration. Such evidence includes the isotopic dilution of the atmosphere and surface oceans with respect to radiocarbon and stable carbon isotopes. In the global carbon cycle there are still considerable uncertainties in our knowledge of the present sources and sinks for the anthropogenically produced CO₂. The total anthropogenic flux to the atmosphere is surrounded by uncertainties. In fact, only the source from fossil fuel combustion is well known, in contrast with the source from land use changes, which is poorly known. The amount of carbon remaining in the atmosphere is the only well known component of the budget. With respect to the oceanic and terrestrial sink, the likely errors are of the order $\pm 100\%$. Many of the uncertainties arise from the lack of adequate data. Another important source of uncertainty is the deficient knowledge of the key physiological processes within the global carbon cycle. The uncertainties can be expressed explicitly by the formulation of a basic mass conservation equation which reflects the global carbon balance, as defined in Equation (6.1):

$$\frac{dC}{dt} = E_{fos} + E_{land} - S_{oc} + I \quad (6.1)$$

where dC/dt is the change in atmospheric CO₂ (GtC/yr), E_{fos} denotes the CO₂-emissions from fossil fuel burning (GtC/yr), E_{land} the CO₂-emissions from changing land use (GtC/yr), S_{oc} represents the CO₂-uptake by the oceans (GtC/yr). Based on best available current knowledge of the sources

and sinks of CO₂, which is a mixture of observations and model-based estimates, it is not possible to obtain a balanced carbon budget. To balance the carbon budget, a rest term is introduced, I , which represents the missing sources and sinks. I might therefore be considered as an apparent net imbalance between the sources and sinks. Table 6.1 presents the global carbon balance over the last decade 1980-1989 in terms of anthropogenic-induced perturbations to the natural carbon cycle. Watson *et al.* (1990) estimate an apparent imbalance between the sources and sinks of 1.6 GtC/yr over this period. This results from a total source of 7.0 ± 1.1 GtC/yr (5.4 ± 0.5 GtC/yr by fossil fuel burning and 1.6 ± 1.0 GtC/yr by land use change) and a total sink of 5.4 ± 1.0 GtC/yr (3.4 ± 0.2 by accumulation in the atmosphere and 2.0 ± 1.0 by oceanic uptake). Three possible reasons are suggested for this imbalance over the last decade: (i) the CO₂-uptake by the oceans is underestimated, (ii) the deforestation in the tropics may be overestimated, (iii) there may be a net uptake by the terrestrial ecosystems at higher latitudes (Watson *et al.*, 1990).

The analysis of the net imbalance in the carbon cycle has become a major issue during the last years, particularly the question how to account for very large carbon sinks in the terrestrial biosphere in the northern temperate latitudes. This interest was stimulated by Tans *et al.* (1990), who suggested that the oceans have taken up no more than 1.0 GtC yearly during the decade of the 1980s (1981 till 1987), making use of an atmospheric transport model with a compilation of observations of air-sea CO₂-difference. This low ocean sink would imply an even larger imbalance, which in this study is attributed to a net carbon sink in the terrestrial ecosystems in the northern temperate latitudes on the order of 1.6-2.4 GtC/yr over the 1980s. The low ocean sink of Tans *et al.* (1990) is less likely, because some of the high latitude ocean sink processes act on time and space scales not resolved in their analysis (Wigley, 1991). Many other studies using tracer-calibrated models estimate an ocean uptake of about 2 GtC/yr. For example, Sarmiento *et al.* (1992)

Table 6.1: Components of the carbon dioxide mass balance (Watson *et al.*, 1990)

Component	1980-1989 (GtC/yr)	
Change in atmospheric mass of CO ₂ (dC/dt)	3.4 ± 0.2	observed
Uptake by the oceans (S_{oc})	2.0 ± 1.0	model-based
Emissions from fossil fuel burning (E_{fos})	5.4 ± 0.5	observed
Emissions from land use change (E_{land})	1.6 ± 1.0	observed
Net imbalance ($I = dC/dt + S_{oc} - E_{fos} - E_{land}$)	-1.6 ± 1.4	

give an estimate of 1.9 GtC/yr for the decade 1980-1989 (which is considered as a lower limit by the authors), making use of a three-dimensional ocean model, which is validated against bomb radiocarbon observations. Quay *et al.* (1992) give an estimate of 2.3 GtC/yr for the period 1970 till 1990, making use of direct measurements of the relative decline in ¹³C/¹²C ratios in dissolved inorganic carbon in the ocean and carbon dioxide in the atmosphere. Furthermore, analyses of Heimann and Keeling (1986), Keeling and Heimann (1986), and Broecker and Peng (1992) indicate a flow of carbon from north to south through the ocean, balanced by a return flux through the atmosphere. The existence of this oceanic carbon pump is also inconsistent with the need of a large terrestrial carbon sink in the Northern Hemisphere, as proposed by Tans *et al.* (1990).

Recent findings with respect to the large terrestrial sink are summarized by the IPCC (Houghton *et al.*, 1992), in which it was stated that: (1) net carbon added to the atmosphere in the tropics is less than expected from deforestation; (2) a strong Northern Hemisphere sink with an oceanic and terrestrial biospheric component, compared to a weak Southern Hemisphere sink must exist; (3) the likeliest terrestrial biospheric processes contributing to large sinks are CO₂ and N fertilization. The latter through increased N deposition due to air pollution and increased fertilizer use could sequester an additional amount of 1.0 GtC/yr during the last decade. Recent work of Kauppi *et al.* (1992), however, shows that the European forests may have been a sink

for carbon in recent decades, but that this is probably not only due to the fertilization effect, but also due to regrowth at middle and high latitudes and improved forest management. The latter in turn may depend on better management and/or regrowth of the temperate and boreal forests or is possibly caused by fertilization of the forest ecosystems in general due to increasing carbon dioxide concentrations in the atmosphere.

These findings underline the importance of negative feedback processes in the global carbon cycle. In carbon cycle models one or more of these feedbacks can be used to balance the global carbon budget (e.g. Goudriaan and Ketner, 1984; Enting and Pearman, 1987; Wigley, 1993). In this study the carbon budget is balanced for the period 1760-1990, by varying model parameters which represent the feedback processes: namely the CO₂-fertilization effect and temperature feedbacks on the rates of net primary production and respiration within the terrestrial biosphere. This is done in an iterative way such that the simulated atmospheric CO₂-values match well with historical estimates from CO₂-measurements of air trapped in ice core bubbles (Barnola *et al.*, 1987; Neftel *et al.*, 1985; Friedli *et al.*, 1986) and, from 1958, with direct measurements at Mauna Loa (Keeling *et al.*, 1989). However, the second possibility (lower deforestation values) is not considered here, because the simulated net CO₂-emissions due to deforestation are already comparatively low, about 1.4 GtC in 1990 (Rotmans and Swart, 1991).

6.3 Methodology

To balance the global carbon budget by incorporating biogeochemical feedbacks the coupled carbon cycle/climate model of IMAGE (experimental version 1.6) is used. The carbon cycle model is extensively described below, and the climate model is described in Chapter 3.

6.3.1 Description of the carbon cycle model

The carbon cycle model of IMAGE (experimental version 1.6) is an extended version of that of Goudriaan and Ketner (1984), and consists of an ocean box-

diffusion model, a terrestrial biosphere model and an atmospheric box model. There are two versions of the carbon cycle model. One standalone version starting in 1760, assuming a steady state initially, before the anthropogenic disturbances are imposed upon the system, and an integrated version incorporated into the framework IMAGE (experimental version 1.6) starting in 1900, with the initial CO_2 concentrations in the various compartments based on the calculations with the standalone version. Here the standalone version is used for the analysis.

The box-diffusion model of the ocean is a slightly modified version of that of Goudriaan and Ketner (1984), see Figure 6.1.

Figure 6.1: Systems diagram of the carbon cycle 12-layer ocean model

Three primary processes are modelled: transport of dissolved carbon by up- and downwelling, through turbulent mixing or vertical diffusion and through precipitation of carbonates. Atmospheric carbon dioxide enters the ocean by gas exchange between the atmosphere and the two surface ocean boxes (at high latitudes a mixed layer (cold water) of about 400 meters, and at lower

latitudes a mixed layer of about 75 meters (and under this one layer of 325 meter)), which are assumed to be well mixed. The chemical processes of gas exchange and equilibrium with CO_2 in the atmosphere are represented by the Revelle differential equation (Björkström, 1979; Rotmans, 1990). Under both mixed layers there are nine layers, with a total depth of 3400 meters.

Figure 6.2: Systems diagram of the j -th ecosystem of the terrestrial biosphere model

The terrestrial biosphere is categorized into seven types of ecosystems: closed and open tropical forest, temperate forest, agricultural and pasture land, human area, and semi-desert or tundra land. Each of these ecosystems is further partitioned into carbon reservoirs such as biomass (leaves, branches, stems, roots, litter, humus and charcoal, so as to represent the stages of cycling of carbon through each ecosystem. The systems diagram for a single ecosystem is given in *Figure 6.2*, where the natural flows of carbon within a particular ecosystem are sketched.

Atmospheric CO₂ is consumed in the process of net primary production and the amount of carbon transferred depends on the area of land allocated to the particular ecosystem and on the rate of exchange of carbon between the biomass reservoir in each ecosystem. The carbon thus consumed is partitioned among the structures of the plant, i.e. the leaves, branches, stems and roots. These biomass pools then decay and the carbon passes through the litter, humus (humification) and charcoal (carbonization) reservoirs, giving off carbon dioxide as part

Table 6.2: Simulated pools and fluxes (in GtC) of the terrestrial part of the global carbon cycle model for 1990.

1990	Trop. closed forest	Trop. open forest	Temp- erate forest	grass land	agri- cultural land	human area	Semi- desert	Total
pools:								
leaves	6.46	2.19	5.62	5.88	4.48	0.08	1.24	25.95
branches	40.86	12.91	18.29	0	0	0.49	2.41	75.00
stems	169.00	67.90	153.53	0	0	2.66	11.35	403.50
roots	40.86	12.91	18.29	3.90	1.12	0.49	1.49	79.10
litter	16.08	4.91	14.30	8.29	3.53	0.36	3.40	50.90
humus	84.28	69.29	270.70	222.60	28.82	12.72	83.44	771.90
charcoal	234.20	95.10	138.13	213.40	71.88	15.41	57.10	825.10
fluxes:								
<i>NPP</i>								
leaves	6.50	2.22	2.83	7.12	5.68	0.08	1.25	25.7
branches	4.33	1.48	1.89	0	0	0.06	0.25	8.0
stems	6.50	2.22	2.83	0	0	0.08	0.25	11.9
roots	4.33	1.48	1.89	4.75	1.42	0.06	0.75	14.7
total	21.70	7.42	9.43	11.87	7.10	0.28	2.49	60.3
<i>litter fall</i>								
leaves	6.46	2.18	2.81	5.88	4.48	0.08	1.24	23.1
branches	4.08	1.29	1.83	0	0	0.05	0.24	7.5
stems	5.63	1.51	2.54	0	0	0.05	0.23	10.0
root decay	2.16	0.68	0.97	2.10	0.60	0.03	0.39	6.9
<i>humification</i>								
root	1.92	0.61	0.86	1.82	0.52	0.02	0.35	6.1
litter	6.43	1.96	4.29	2.48	0.71	0.09	1.02	17.0
<i>carbonization</i>								
decomposition	0.42	0.14	0.27	0.28	0.06	0.01	0.08	1.3
litter	9.65	2.95	2.86	1.66	2.83	0.09	0.68	20.7
humus	8.0	2.63	5.14	5.28	1.10	0.24	1.59	24.0
charcoal	0.47	0.19	0.28	0.43	0.14	0.03	0.11	1.7

of the decay process, and returning carbon to the atmosphere. These natural processes are modelled as exponential decay, and are essentially linear (natural decomposition).

Imposed on this natural system is a reallocation of land areas through human activities like agriculture, shifting cultivation, commercial wood production, cattle breeding, fuelwood gathering, burning of forest, reafforestation and industrial activities. This affects the various carbon pools differently, and also acts to transfer humus, litter and charcoal to different land uses. In *Table 6.2* the simulated sizes of the pools and fluxes for each of the ecosystems are presented for 1990. Next to the natural carbon flows, *Figure 6.2* also shows the anthropogenic component, represented by arrows flowing out to the right, indicating the flow of carbon to carbon pools in the other ecosystems. The skew lines of *Figure 6.2* denote the corresponding flows from the other 6 ecosystems back into this ecosystem (humification and carbonization processes).

The land use change model, consisting of a socio-economic module and a land use cycling module, is represented by the systems diagram of *Figure 6.3*, for each of the continents of Africa, Latin America and South East Asia. All converted forests are assumed to end up as agricultural or pasture land, degraded land and semi-desert, or re-established forests (by reforestation).

Deforestation is triggered by a variety of processes, which are mainly caused by a number of demands driven by growth of population and economy, see *Figure 6.3*. At any time the expansion of agricultural land, both as permanent agriculture and shifting cultivation, is distributed over the ecosystems closed and open tropical forests and other land (semi-desert or tundra land). This distribution mechanism is done according to soil suitability, estimated by Bouwman (1989) and presented in Swart and Rotmans (1989). The expansion of pasture into closed and open tropical forest is distributed according to the ratio between the initial and current amount of closed and open tropical forest. The impact of logging on tropical deforestation is assumed to be proportional to the expected growth rate of hardwood

production and the harvesting efficiency. Reforestation is included by scenario-dependent logistic functions. Deforestation through fuelwood gathering is taken proportional to the rural population growth. Although it is very difficult to estimate, an attempt was made to quantify the impact of industrial, mining or infrastructural projects. The processes which generate the demand, how the demand is met, and the subsequent associated processes, are all described in detail in Rotmans and Swart (1991).

The simulated land use changes lead to gradual transitions of one parcel of land of one ecosystem to another. In the model this exchange of land between the ecosystems is represented by a time dependent land transfer matrix of which the elements indicate the annual transfers of land from one ecosystem to another. Shifting from an ecosystem which contains much carbon to one with little carbon, as is the case with deforestation, results in a net release of CO₂ from the terrestrial biota to the atmosphere.

The net release of CO₂ resulting from conversion of tropical forest land into another ecosystem depends on the area transferred, the carbon density in biomass and litter of the ecosystems considered and the amount of carbon in biomass and litter that is channelled to the atmosphere (determined by carbonization and humification fractions). The total deforestation flux equals then the sum of the contributions from the conversions of areas of tropical forests into agricultural and pasture land, and human and semi-desert/tundra area.

6.3.2 Model description of the terrestrial feedback used

Introduction

Enhanced atmospheric CO₂-concentrations and increased temperatures affect various components of a plant's carbon budget, including: photosynthesis, respiration, biomass accumulation and allocation (Melillo *et al.*, 1990). A more general description of these biogeochemical feedbacks is given in Watson *et al.* (1990), Lashof (1989) and

Figure 6.3: Systems diagram of the land use categories and processes in the land use change model

Harvey (1989b). This study only considers the following terrestrial feedback processes: the CO_2 -fertilization effect and the temperature effects on net primary production and respiration of soil and litter. Although a highly parameterized oceanic feedback on vertical diffusion and an ocean temperature/chemistry feedback is already implemented in the model (den Elzen *et al.*, 1991; den Elzen and Rotmans, 1993), no variations of these oceanic feedbacks are presented in this study. This because of the extreme uncertainties of the feedback concepts in the ocean, and also because the first experiments with these positive feedbacks in the coupled carbon cycle/climate model showed the effects to be negligible in comparison with some of the terrestrial feedbacks. Figure 6.4 gives an overview of the terrestrial feedbacks modelled in the coupled carbon cycle/climate model. Below the modelling backgrounds and assumptions of the various terrestrial

feedbacks is described, which are incorporated in the model.

Carbon dioxide fertilization

Short-term experiments under controlled conditions show for most plants an increasing photosynthetic rate, water use efficiency and plant growth (thus fixing more carbon) at enhanced CO_2 -levels (Strain and Cure, 1985). The few experiments done at the ecosystem level, however, show a diverse response. The response of a single species is shown to become highly modified at the ecosystem level, and is not representative for the response of a whole ecosystem (Bazzaz, 1990). If increased CO_2 -concentrations enhanced the productivity of natural ecosystems, more carbon may be stored in woody-tissue or soil organic material. In general the response of forests, with their high contribution to global

Figure 6.4: Biogeochemical feedbacks within carbon cycle

photosynthesis, is of high importance (Luxmoore *et al.*, 1986), but so far no experiments have yet been done in forested systems.

The CO₂-fertilization process is modelled by using the logarithmic relationship between elevated CO₂ and net primary production ($NPP(t)$), as used by Gifford (1980) and Goudriaan and Ketner (1984). In this relationship the global biotic growth factor (or fertilization factor) β reflects the fractional increase in $NPP(t)$ due to an increase in atmospheric CO₂-concentration.

$$\frac{dNPP(t)}{NPP_{ic}} = \beta * \frac{dpCO_2(t)}{pCO_2(t)} \quad (6.2)$$

where $dNPP(t)$ is the change in net primary production at time t (GtC/yr), NPP_{ic} the initial primary production in 1760 (GtC/yr), β the biotic growth factor, $dpCO_2(t)$ the change in the atmospheric CO₂-concentration at time t (ppmv/yr) and $pCO_2(t)$ the atmospheric CO₂-concentration at time t (ppmv). Although the terrestrial biota model is divided into seven ecosystems, only one, global, β -factor is used here for the net primary production. The value of this β -factor varies greatly in the different carbon cycle models, because it is usually used as a tuning factor to get a balanced carbon budget. Kohlmaier *et al.* (1989) decouple soil and litter respiration and net primary production, and let a global β -factor ($= 0.375 \pm 0.225$) affect both processes. Goudriaan and Ketner (1984) use a β -factor of 0.5, necessary to reproduce the measured atmospheric CO₂-trend over the period 1958 to 1980. Bacastow and Keeling (1973) indicate a range of 0.2 to 0.6 for simulating the correct CO₂ build-up over the period 1959 to 1969. Experiments on single plants in greenhouses under optimal supply of nutrients, show values of the biotic growth factor up to 0.7 (Goudriaan and de Ruiter, 1983). At such ideal growing conditions Gates (1985) measured a β -factor of 0.5-0.75 for a variety of plants at 340 CO₂ ppmv, decreasing to 0.3-0.5 at 680 ppmv. Taking into consideration the foregoing estimates of the β -factor, and after having compared the modelling results with the observed atmo-

spheric CO₂-values by a trial and error analysis, a 'best guess' or 'central estimate' value of 0.4 is adopted here, with an uncertainty range of 0.1 to 0.5.

Temperature feedbacks

This study only takes account of two terrestrial temperature feedbacks: the temperature feedback on the net primary production (net photosynthesis minus respiration of non-photosynthetic plant parts) and the temperature feedback on the respiration of soils and litter. A global temperature increase results in an increasing net primary production (negative feedback), while the effect on soils and litter respiration will be a release of carbon to the atmosphere (positive feedback). A key point of discussion in the literature is the sign of the total temperature effect on respiration and net primary production (see e.g. Harvey, 1989b). Watson *et al.* (1990) state that the temperature effect on respiration will dominate the temperature effect on the net primary production, and thus will amplify global warming. Estimates of this additional flux vary from one to a few GtC per year. Recently Jenkinson *et al.* (1991) underscored the potential importance of this enhanced soil respiration feedback.

In many regions, however, the effects of precipitation changes and moisture availability are at least as important as the temperature effects on net primary production. Because it is currently impossible to project future precipitation in a global way here no precipitation related feedbacks are considered, although this is a serious short coming of this approach.

Harvey (1989b) considers a temperature feedback on the net photosynthesis and a temperature feedback on the translocation of non-photosynthetic products from non-woody to woody tree parts. In the analysis both feedbacks are embedded in the temperature feedback on the net primary production. In the carbon cycle model, the net primary production is partitioned among the four major components: leaves, branches, stems and roots according to fixed partitioning coefficients (Goudriaan and

Ketner, 1984). The temperature effect on these coefficients, also a part of the temperature feedback on translocation, as proposed by Harvey (1989b), is assumed to be negligible.

Net Primary Production Both photosynthesis and respiration are stimulated by a temperature increase. The magnitude of this effect is dependent on the temperature domain. Above 0 °C, gross photosynthesis initially responds rapidly to temperature, but slows down in the optimum range (20-35 °C). In contrast, the response of respiration is relatively slow below 20 °C, but at higher temperatures it accelerates rapidly up to 40 °C (Melillo *et al.*, 1990). As a result of these processes the response of the net photosynthesis to temperature increases from zero to an optimum value (at 20-35 °C), and then decreases to zero at higher temperatures.

The general response of plant growth shows a similar response (Fitter and Hay, 1981). Although the processes of photosynthesis and respiration are described by a parabolic and exponential function of temperature, respectively, here the temperature-dependence of these metabolic processes is taken to be exponential for both and is expressed by a Q_{10} -value, indicating the rate of increase of each process at a 10 °C temperature rise. This Q_{10} formulation is assumed to be valid, while the temperature changes are small compared to the present climate. The temperature effect on net primary production is modelled by adding to Equation (2) the Q_{10} -value and the global averaged surface temperature increase at time t ($\Delta T_s(t)$):

$$NPP(t) = NPP_{ic} * \left(1 + \beta * \ln \frac{pCO_2(t)}{pCO_{2,ic}}\right) * \exp\left(\frac{\Delta T_s(t)}{10} \ln Q_{10}^{npp}\right) \quad (6.3)$$

where $pCO_{2,ic}$ denotes the initial atmospheric CO_2 -concentration (in 1760) (ppmv).

To account for spatial variations in temperature, Q_{10} is allowed to be temperature dependent. To do this, photosynthetic and respiration response data of Fitter and Hay (1981) have been schematized, by

defining eight different temperature domains of 5 degrees, represented as [1...5], ..., ..., [36...40] °C, respectively. The $Q_{10}^{npp}(\tau)$ then represents the Q_{10} -value for net primary production, valid within the temperature range τ , where τ indicates the eight different temperature domains of 5 degrees. Using the NPP data of Olson *et al.* (1983), and den Elzen *et al.* (1991) derive the following Q_{10} -value for net primary production:

$$Q_{10}^{npp} = \left[\sum_{\tau=1}^8 NPP_{ic}(\tau) * Q_{10}^{npp}(\tau) \right] / NPP_{ic} \quad (6.4)$$

where $NPP_{ic}(\tau)$ (GtC/yr) is the initial net primary production of all territories where the average annual temperature lies within the temperature range τ . The resulting weighted average Q_{10} -value (Q_{10}^{npp}) for the net primary production is 1.4. Many others have derived Q_{10} -values for net primary production. Harvey (1989b), for instance, assumed an effective Q_{10} -value for net primary production of 1.4, based on a Q_{10} -value for the net photosynthesis of non-woody tree parts of 1.53 and a Q_{10} -value for the respiration of woody tree parts of 2.0. Other estimates vary between 1.0 to about 2.0, also dependent on the temperature domain and type of ecosystem considered (Webb *et al.*, 1983; Esser, 1987; Kohlmaier *et al.*, 1990). Given these reported values, a range of Q_{10} -values, from 1.0 to 2.0 (see Table 6.3) is considered here, with a central estimate value of 1.4.

Litter and soil respiration - The Q_{10} -value for the soil and litter respiration varies greatly in the literature. Kohlmaier *et al.* (1990) estimate the Q_{10} -value of this respiration between 1.3 and 4.0, substantially more than the Q_{10} -value for net primary production. Harvey (1989b) adopts a Q_{10} -value of 2.0, with an uncertainty range from 0.77 to 3.1, where the smaller values correspond with lower moisture availability. Based on these estimates a central estimate value of 2.0 is used here, with an uncertainty range between 1.0 and 3.1 (Table 6.3).

In the model the litter and soil respiration directly affects the net ecosystem production ($NEP(t)$), which is the net growth of an

Table 6.3 'Best guess' or 'central estimate' values and uncertainty ranges for the various feedback parameters

Feedback parameter	Min	Central Est.	Max
Q_{10}^{NPP} = factor by which the net primary production increases for a 10 °C temperature increase	1.0	1.4	2.0
Q_{10}^{res} = factor by which the litter and soil respiration increases for a 10 °C temperature increase	1.0	2.0	3.1
β = fertilization factor	0.0	0.40	0.5

ecosystem:

$$NEP(t) = NPP(t) - (dL(t) + dH(t)) \quad (6.5)$$

$$\cdot \exp\left(\frac{\Delta T_s(t)}{10} \ln Q_{10}^{res}\right) - dC(t) - dB(t)$$

where $dL(t)$, $dH(t)$, $dC(t)$ and $dB(t)$ denote, for each ecosystem, the decay of litter, humus, and charcoal, and the changes in biomass by the decay of roots at time t (GtC/yr), respectively. Q_{10}^{res} represents the Q_{10} -value for the respiration of soils and litter.

6.4 Results

6.4.1 Past CO_2 -concentration changes

To examine the role of the feedbacks modelled, this study uses the historical concentration values of carbon dioxide, from 1760 to 1958, as indicated from measurements on air trapped in ice from Siple Station, Antarctica (Neftel *et al.*, 1985; Friedli *et al.*, 1986), and measured at Mauna Loa from 1958 to 1990 (Keeling *et al.*, 1989). As a first experiment the model is run with no feedbacks. The resulting simulated atmospheric CO_2 -values are depicted in Figure 6.5, together with the observed CO_2 -values. Comparing both trends shows us that the simulated atmospheric CO_2 -concentrations are higher than the observed concentrations, implying an apparent imbalance in the model. In 1990 the simulated CO_2 -

concentration is 374 ppmv, whereas the observed annual average value for 1990 is 353 ppmv (Watson *et al.*, 1990). For the period 1850-1990 (the starting year 1850 is chosen, because this year is also used by Watson *et al.* (1990) in their cumulative carbon fluxes) there is an apparent imbalance of carbon of about 44 GtC in the model (see Table 6.4). Wigley (1993) obtains a central value for the imbalance of about 80 GtC over 1850-1989. This difference can be explained by the higher estimates of land use changes (123 GtC, based on the 1850-1986 estimate of Watson *et al.* (1990)) and lower ocean uptake (113 GtC) in Wigley's model. Over the 1980s (1980-1989) the model gives an annual apparent imbalance of about 0.85 GtC, which must be stored either in the oceans or in the terrestrial biosphere.

From this experiment it can be concluded that the observed values can be simulated with the model only if an additional sink is introduced. Therefore for this unbalanced case the global fluxes between the oceans and the atmosphere, and the terrestrial biosphere and the atmosphere are examined. Figure 6.6 shows the global fluxes produced by the model which represent the CO_2 -uptake by the oceans, the net release of CO_2 due to land use changes (encompassing deforestation) and the emissions of CO_2 by fossil fuel combustion. Analysing these fluxes shows that, when running the model with no feedback processes, the ocean CO_2 -uptake, directly obtained from the model, is rather high (approximately 2.5 GtC/yr during the 1980s, being higher than the sparsely

Table 6.4: Components of the modelled carbon dioxide mass balance of this study with and without feedbacks

Component	1980-1989 (GtC/yr)		1850-1989 totals (GtC)	
	no feedbacks	with feedbacks	no feedbacks	with feedbacks
Observed change in atm. CO ₂ (dC/dt) ^a	3.4	3.4	144	144
Modelled change in atm. CO ₂ (dC/dt) ^b	4.25	3.4	188	144
Uptake by the oceans (S_{oc})	2.5	2.15	135	117
Emissions from fossil fuel burning (E_{fos})	5.4	5.4	219	219
Emissions from land use change (E_{land}) ^c	1.35	0.15	104	45
Apparent net imbal. ($I=dC/dt+S_{oc}-E_{fos}-E_{land}$)	-0.85	0.0	-44	-3

^a The historical concentration values of carbon dioxide from 1750 to 1958 are based on measurements on air trapped in ice from Siple Station, Antarctica (Neftel *et al.*, 1985a; Friedli *et al.*, 1986), and from 1958-1989 measured at Mauna Loa (Keeling *et al.*, 1989).

^b In the model calculations this net imbalance is stored in the atmosphere, leading to higher CO₂-concentrations than the observed values over the historical period.

^c In the case of feedbacks: E_{land} is the net terrestrial ecosystem emissions.

measured ocean uptake of CO₂). The cumulated oceanic CO₂-flux over the period 1850-1990 is 135 GtC, which is also relatively high compared to the central value of 113 GtC given by Wigley (1993) (see Table 6.4, case without feedbacks). On the other hand, the magnitude of the terrestrial flux to the atmosphere generated by the model is about 1.35 GtC/yr during the 1980s. The cumu-

lated land use flux over 1850-1990 amounts to 104 GtC, which is lower than Wigley's central estimate value of 123 GtC based on Watson *et al.* (1990). The simulated land use flux in Figure 6.6 shows a trend which is similar to the biospheric carbon flux presented by Houghton and Woodwell (1989); although, in general, the magnitude of the simulated flux is somewhat smaller

Figure 6.5: Atmospheric CO₂-concentration over the period 1760 to 1990 (no feedbacks)

— no feedbacks
 - - - observed values

Figure 6.6: Components of the carbon budget over the period 1760 to 1990 (no feedbacks)

than that of Houghton and Woodwell. This may be due to our maybe too conservative socio-economic assumptions which trigger the land use changes in the land use change model. These results indicate that, under the condition that the sources are not changed in the model, the surplus of carbon should be stored by the creation of a terrestrial sink in the model, rather than by raising the already high CO₂-uptake of the oceans.

These conclusions lead us to experiments in which the role of feedback processes is explored. For these experiments the central

estimate values for the various feedback parameters are chosen, which are based on recent literature for the temperature related feedbacks and on a trial and error balancing analysis for the fertilization feedback,

Table 6.3 shows the central estimate values as well as uncertainty ranges considered here for the various feedback parameters. Starting with the observed value at $t = 0$, and taking the central estimate values, the simulated curve fits well with the observed atmospheric CO₂-concentrations, as is shown in Figure 6.7.

Figure 6.7: Atmospheric CO₂-concentration over the period 1760 to 1990 (with feedbacks)

Figure 6.8: Components of the carbon budget over the period 1760 to 1990 (with feedbacks)

Table 6.4 summarizes the simulated values of the different components of the carbon dioxide mass balance for the 1980s, as well as the cumulated values over the period 1850-1989. This Table shows that, when feedbacks are taken into account, the carbon budget balances over the 1980s, which implies that the CO_2 -flux resulting from modelled feedbacks is about 0.85 GtC/yr (i.e., the apparent net imbalance of the carbon budget when no feedbacks are considered). It should be noted, however, that the balance is not perfect, but rather quite close. For example, the relative difference between observed and modelled atmospheric CO_2 during the 1980s is about 0.25% (or 1 ppmv). If in the following the difference is on that order of magnitude, it is denominated as 'well-balanced'. Over the period 1850-1990 the cumulated flux due to the feedbacks (CO_2 -fertilization effect) amounts to 44 GtC, i.e. the apparent net imbalance in the case without feedbacks). Global fluxes for the period 1760-1990 are pictured in Figure 6.8. Taking account of the terrestrial feedbacks leads to a global terrestrial biosphere flux that is much smaller than in the unbalanced case (Figure 6.6). The biospheric carbon flux shows a decreasing trend in the 20th century, which is in contrast with the biospheric flux estimates of Houghton and Woodwell (1989), but within the uncertainty range of the past net bio-

spheric emissions given by Siegenthaler and Oeschger (1987). Houghton and Woodwell (1989), however, do not take into account the potential carbon uptake by CO_2 -fertilization, while Siegenthaler and Oeschger (1987) estimate the net biospheric flux including possible feedbacks. Comparing the simulated model flux estimates with those of Wigley (1991) gives a similar pattern. Over the period 1900-1980, Wigley (1991) estimates a biospheric flux of only 14 GtC, while the model gives about 20 GtC. For the period 1960-1980 the model generates a net biospheric CO_2 sink, which is comparable with the net biospheric sink over the interval 1950-1983 presented by Wigley (1991). In this balanced case the simulated ocean flux is now around 2.15 GtC/yr during the 1980s, which is in better accordance with Watson *et al.* (1990).

6.4.2 Future CO_2 -concentration projections

Now the future atmospheric CO_2 -concentrations for the IPCC-1990 Business-as-usual scenario (hereafter BaU90 scenario) are calculated, which is described in detail in IPCC (1991b) and Chapter 5. Again these calculations assume for the feedback parameters the central estimate values, since these lead to a well-balanced carbon budget over the period 1760-1990. Starting with a well-balanced budget in 1990, the atmo-

spheric CO₂-concentrations for the BaU-1990 scenario are compared with the IPCC-results (*Figure 6.9*). Furthermore an uncertainty range is presented in this Figure which is based on variations of the feedback parameters and ocean fluxes. This means that the feedback parameters and ocean fluxes are set on their minimum or maximum levels (see *Table 6.3* and *Table 6.7*, of which the latter is explained in the section on sensitivity experiments). The sets of parameter combinations used here result in a well-balanced carbon budget, so they represent a balanced uncertainty range. The simulated central estimate value is lower than the IPCC-value: in 2100 the simulated CO₂-concentration is 761 ppmv, while the IPCC's central estimate is 827 ppmv, a difference of approximately 16% from the 1990 level. The scenario assumptions used here for the BaU-1990 scenario are similar to those made by the IPCC (IPCC, 1991b). The fossil fuel inputs are equal to the IPCC-values, while the socio-economic assumptions in the land use change model (described in Rotmans and Swart, 1991) are such, that the simulated net deforestation trend is comparable with the (rather strange) IPCC-1990 deforestation trend. This is shown in *Figure 6.10*. The cumulated difference between the two deforestation curves amounts to 13 GtC, or 6 ppmv. This implicates that only a small part

of the difference in future atmospheric CO₂-concentrations can be explained by the difference in input data. This leads to the conclusion that the major part of the difference is due to the fact that the IPCC-estimates are based on models that either have an unbalanced carbon budget, or if they are balanced, the simulated terrestrial fluxes do not match well with the observed values. Most models used by the IPCC ignore feedback processes. Therefore these models require a somewhat unrealistic total source of CO₂ of 6.2 GtC in 1990, while the present value is probably around 8 GtC (*Table 6.3*). Ignoring these feedback mechanisms leads to overestimated future CO₂-concentrations as pointed out by Wigley and Raper (1992).

For the central estimate parameters the different carbon budget components (ocean flux, fossil fuel emissions and land use change flux) are presented in *Figure 6.11*. *Figure 6.12* presents the corresponding total amounts of carbon sequestered in reservoirs such as biomass (leaves, branches, stems, roots), litter, humus and charcoal. The simulated carbon content in the biomass pool shows a decreasing trend, since the decay processes and litter fall dominate the net primary production. The carbon content in the litter pool slightly decreases (although it looks constant in *Figure 6.12*), because the flow out of the litter pool through decay

Figure 6.9: Atmospheric CO₂-concentration for the IPCC-1990 Business-as-Usual scenario; the uncertainty range is based on a variation of the feedback parameters

■ uncertainty range
— feedbacks
(central estimates)
- - - IPCC-values

Figure 6.10: Net CO₂ emissions due to deforestation for the IPCC-1990 Business-as-Usual scenario over the period 1990 to 2100

processes and litter humification is larger than the input flow by biomass.

For humus and charcoal, the input sources by humification and carbonization dominate the output flows (decay processes and carbonization). This leads to an increasing trend in the carbon storage in humus and charcoal. The fairly high carbonization factors in the model, combined with a large turnover time of 500 years, cause a relatively large (semi)-sink of carbon in the form of a charcoal pool. This results in a very slow

decay of the charcoal pool. The storage of carbon in the different reservoirs is summarized in Table 6.5, which gives the components of the carbon dioxide mass balance, cumulated over the period 1990-2100 for the case with feedbacks and with no feedbacks. The latter is treated in the section that deals with the sensitivity analysis.

For the case with feedbacks the resulting net airborne fraction, defined as the fraction of the total CO₂ emissions from fossil fuels and terrestrial biosphere that remains in the

Figure 6.11: Components of the carbon budget over the period 1990 to 2100 for the IPCC-1990 Business-as-Usual scenario (with feedbacks)

Table 6.5: Components of the modelled carbon dioxide mass balance of this study with and without feedbacks for the period 1990-2100

Component	1990-2100 totals (GtC)	
	no feedbacks	with feedbacks
Change in atmospheric CO ₂ mass (dC/dt)	1085	865
Uptake by the oceans (S_{oc})	570	515
Emissions from fossil fuel burning (E_{fos})	1500	1500
Emissions from land use change (E_{land})	155	- 120
Net imbalance ($I = dC/dt + S_{oc} - E_{fos} - E_{land}$)	0	0

atmosphere (Rotmans, 1990), is represented in Figure 6.13.

Finally, Figure 6.14 the simulated CO₂ concentrations for the four IPCC-1990 scenarios are compared with the IPCC-results. In 2100 the simulated CO₂ concentration and the IPCC 'central estimate' values show differences from about 16% for the BaU90 scenario till about 22% for the AP90 scenario, compared to the 1990 level.

6.4.3 Sensitivity analysis

A number of sensitivity analyses have been performed with previous versions of the coupled carbon cycle/climate model (which contained only one feedback process, the fertilization effect, represented by a global

biotic growth factor, or fertilization factor), using statistical techniques (Rotmans, 1990). The set of techniques used for the sensitivity analyses consists of least squares curve fitting, regression analysis, and factorial designs. A detailed description of how to use these techniques is given in Kleijnen *et al.* (1992). These studies indicate the importance of the fertilization factor, and to a lesser extent the charcoal fractions, humification factors and the residence times of humus. The present version of the coupled carbon cycle/climate model includes more feedbacks, and was not yet subjected to a complete sensitivity and uncertainty analysis. To investigate to what extent the terrestrial feedbacks affect the outcomes a simple one-factor sensitivity analysis is carried out, by varying one

Figure 6.12: Modelled carbon contents of biospheric components for the IPCC-1990 Business-as-Usual scenario

Figure 6.13: Airborne fraction for the IPCC-1990 Business-as-Usual scenario

feedback parameter at a time for the period 1990 to 2100. The results are presented in Table 6.6.

It should be noted that the temperature related terrestrial feedbacks are triggered by a global temperature increase of about 3 °C for the period 1990-2100, calculated by the model. In the first run the feedbacks are switched off, resulting in a simulated CO₂-concentration of 865 ppmv in 2100. For this case the cumulated carbon storage in the different reservoirs is given in Table 6.5. The

high atmospheric CO₂-concentration in 2100 (865 ppmv) or compared to the IPCC-value (827 ppmv) can be explained by the large flux of CO₂ from land use changes (155 GtC). Switching on the feedbacks leads to a considerably lower atmospheric CO₂-concentration of about 761 ppmv, mainly caused by the net CO₂-uptake of 120 GtC by the terrestrial biosphere and the soils. The emissions have primarily gone into the temperate and tropical forests, with a partitioning between about 30% in biomass, 55%

Figure 6.14: Atmospheric CO₂-concentration for the four IPCC-1990 scenarios (with feedbacks)

- IPCC-1990 Business-as-Usual scenario
- - - IPCC-1990 Low emissions scenario
- ... IPCC-1990 Control Policies scenario
- . - IPCC-1990 Accelerated Policies scenario

Table 6.6: One-factor sensitivity analysis

	Run 0	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9	Run 10
Q_{10}^{np}	1.4	1.0	1.4	1.0	1.0	1.0	2.0	1.4	1.4	1.4	1.4
Q_{10}^{res}	2.0	1.0	1.0	2.0	1.0	2.0	2.0	1.0	3.1	2.0	2.0
β	0.4	0.0	0.0	0.0	0.4	0.4	0.4	0.4	0.4	0.0	0.5
pCO_2^a	761	865	821	918	756	805	712	712	790	875	736

^a pCO_2 is the simulated atmospheric CO₂-concentration in the year 2100 (in ppmv)

in humus, 5% in litter, and 10% in charcoal.

In the next three experiments (runs 2, 3 and 4) the model is run by setting only one feedback parameter on its central estimate value, ignoring other feedbacks. In the following six experiments (runs 5 to 10) one feedback parameter is set on its maximum or minimum value, fixing the other feedback parameters on their central estimates. These experiments show that the CO₂-fertilization feedback effect appears to be dominant (runs 4, 9 and 10), while the photosynthetic and plant respiration effect seems to counter-balance the soil and litter respiration effect (runs 2, 3, and 5 to 8). This means that in the model the temperature effect on biomass growth and on the decrease of carbon in soils is about equal.

The next sensitivity experiments are meant to produce well balanced carbon budgets for various combinations of feedback parameters and ocean fluxes for the whole period 1760-2100. Table 7 shows the different combinations of the feedback parameters and ocean fluxes and the resulting atmospheric CO₂-concentrations. In order to quantify the ‘goodness of balance’ for the different balancing experiments the root mean square concentration error (rmse) is calculated for the period 1760-1990. The concentration error is the difference between the modelled and the observed atmospheric CO₂-concentrations. The rmse value indicates a measure of the dispersion of modelled CO₂-concentrations around the observed. The differences between the different rmse values turn out to be small, certainly in comparison

with the value of 5 for the ‘no feedbacks’ case. The Table also gives the relative difference between the rmse and the root mean square observed concentrations, which are between 0.1-0.2% (1.5% for the ‘no feedbacks’ case).

In the first four runs (run 1 to 4) only the terrestrial feedback parameters are varied in order to get a balanced carbon budget. These experiments result in outcomes which lie between 747 and 762 ppmv. In particular run 2 shows that the fertilization effect largely determines the historical balance; for this case the resulting atmospheric CO₂-concentration in 2100 of 760 ppmv is about the same as the simulated value of 761 ppmv for the central estimate case. In runs 9 and 10 the atmosphere-ocean flux during the 1980s is varied between 1.5 and 2.7 GtC/yr, which is in between the upper and lower boundaries (between 1 and 3 GtC/yr during the 1980s) given by Watson et al. (1990), by varying the diffusivity and the rate of precipitation of organic material. Table 7 shows that variations in the ocean flux strongly influence the projected CO₂-concentration range in the model.

The uncertainty range following from these balancing experiments was already presented in Figure 6.9. In Figure 6.9 an uncertainty is presented due to a number of variations of feedback parameters and ocean flux which lead to a well balanced carbon budget, ranging from about 670 ppmv to about 815 ppmv.

In spite of all uncertainties which surround the global carbon cycle, the results

Table 6.7: *Balancing sensitivity experiments*

	Run 0	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6
Q_{10}^{np}	1.4	2.0	1.0	2.0	1.2	1.8	1.4
Q_{10}^{res}	2.0	3.1	1.0	1.0	2.5	1.2	2.5
β	0.4	0.35	0.4	0.1	0.5	0.5	0.1
rms	0.4	0.4	0.45	0.68	0.35	0.7	0.6
rel. ^a	0.13	0.13	0.14	0.22	0.11	0.22	0.19
dC/dt^b	3.4	3.4	3.35	3.5	3.3	3.4	3.4
S_{oc}^c	2.2	2.2	2.2	2.2	2.2	1.5	2.7
E_{land}^b	0.15	0.15	0.1	0.3	0.0	-0.5	0.7
E_{fos}^b	5.4	5.4	5.4	5.4	5.4	5.4	5.4
pCO_2^d	761	751	760	747	762	670	815

^a relative difference between the rms value and the rms of the observed concentration (%).

^b for the period 1980-1989 (in GtC/yr)

^c S_{oc} is the simulated atmosphere-ocean flux during the 1980s (in GtC/yr)

^d pCO_2 is the simulated atmospheric CO_2 -concentration in the year 2100 (in ppmv)

obtained from experiments with the model are of interest. The first point of interest is that, if the atmosphere-ocean flux is kept identical, the fertilization feedback determines the balancing and dominates the temperature related feedbacks. To put it differently, balancing by changing only the fertilization feedback gives similar results in terms of future atmospheric CO_2 -concentrations as balancing by changing both fertilization and temperature feedbacks. The second is that variations in the atmosphere-ocean flux strongly influence the balancing, and thus the projected CO_2 -concentration. Balancing by changes in both ocean flux and fertilization feedback will lead to different historical biospheric fluxes, resulting in substantially different atmospheric CO_2 -projections, which was also pointed out by Harvey (1989a) and Wigley (1993).

6.5 Conclusions

Although not pretending to give a comprehensive picture of the potential role of the biogeochemical feedbacks within the

carbon cycle, this study tries to evaluate the role of some terrestrial biospheric feedbacks in balancing the carbon budget. Simulation experiments with a coupled carbon cycle/climate model show that excluding feedbacks in the model leads to an apparent net imbalance in the past and present carbon budget. For the period 1850-1990 there is an apparent imbalance of carbon of about 44 GtC in the model. Over the 1980s the model produces a yearly imbalance of about 0.85 GtC. From these experiments it follows that in the model a balanced carbon budget can only be created if a terrestrial sink is introduced. In order to create balanced carbon conditions for the period 1760-1990 the CO_2 -fertilization effect and the temperature related feedbacks on net primary production and respiration of soil and litter are incorporated in the model. Although these feedbacks are only parameterized representations of very complicated biogeochemical processes and should be modelled in a spatially-explicit manner, it seems to be a reasonable first step in considering the role of feedback processes in the carbon cycle, given the uncertainties and the lack of

geographically-defined data.

Choosing so-called 'central estimate' values for the feedback parameters, which are based on current insights from recent literature and partly on trial and error balancing experiments, leads to a well balanced carbon budget. This implies that the balance is quite close, but not perfect (a perfect balance cannot be created with the forward modelling approach). The resulting historical biospheric flux falls within the uncertainty range of the past net biospheric emissions presented in recent literature. For the period 1960-1980 a net biospheric sink is generated by the model, which is in accordance with results of other carbon cycle models.

Sensitivity experiments show that in the model a well balanced carbon budget can be obtained in many different ways. The fertilization feedback appears to determine the balancing and dominates the temperature related feedbacks, while the net primary production feedback seems to counter-balance the soil and litter respiration feedback effect. It is also shown that variations in the atmosphere-ocean flux strongly influence the balancing. Different balances by changing the atmosphere-ocean flux and the fertilization feedback lead to different historical biospheric fluxes and to different

atmospheric CO₂-projections.

Future projections based on the IPCC-1990 Business-as-Usual scenario show that the estimated CO₂-concentrations are considerably lower than the IPCC-values: in the year 2100 the estimate is 761 ppmv, whereas the 'central estimate' value of the IPCC is 827 ppmv. This is mainly due to the dominating role of the fertilization feedback effect. As shown in this study the differences in input data cannot account for this significant difference of about 16% from the 1990 level. The difference can be explained by the fact that most global carbon cycle models used by the IPCC were unbalanced, while the balanced models do not produce terrestrial fluxes that correspond to observations. The imbalance in the models that the IPCC used is caused by the fact that feedback processes, which must be included in order to obtain balanced conditions, are ignored in these models. This results in overestimated future atmospheric CO₂-concentrations.

Finally, sensitivity analysis experiments show that, under the condition of a balanced carbon budget, the IPCC's central estimate of 827 ppmv falls beyond the estimated uncertainty range of [670 to 815] ppmv, based on variations of both modelled terrestrial feedback parameters as well as the ocean flux.

7

An analysis of the sources and sinks of methane in the CH₄-CO-OH cycle

This Chapter is based on: Rotmans, J., Elzen, M.G.J. den, Krol, M., Swart, R.J., Woerd, H.J. van de (1992): Stabilizing atmospheric concentrations: towards international methane control. Ambio Vol. 21, no. 6, 404-413, and also partly on: Elzen, M.G.J. den, and Rotmans, J. (1993): Modelling climate related feedback processes. International Journal of Health and Environmental Sciences, in press.

7.1 Introduction

Comprehensive global measurements of atmospheric methane concentrations show that methane levels are increasing substantially. From the perspective of global climate change this is important because methane is a major greenhouse gas, second only to carbon dioxide. Furthermore, increasing methane concentrations will change the distribution and concentration of tropospheric ozone, affecting directly the oxidizing capacity of the free troposphere. Therefore, methane emissions must be controlled and atmospheric methane must be stabilized.³ So far, world wide discussions on the level and timing of response measures with respect to delaying climate change, focus on more manageable substances, like CO₂ and CFCs. Little attention has yet been paid to the other trace gases such as methane and nitrous oxide, because of uncertainties in their sources and sinks. Nevertheless, during the 1980s they caused approximately 30% of the calculated climate change, of which methane contributed about 13% (Shine *et al.*, 1990). These estimates are based on the direct radiative forcing caused by concentration changes over the period 1980-1990. Such estimates, however, do not accurately reflect the relative impact of a given quantity of emissions over a longer time period. The concept of Global Warming Potential (GWP) of emissions of greenhouse gases for the account of differences in atmospheric lifetimes and indirect impacts of emissions (see also Chapter 15). Calculations based on these GWPs show that the relative climate effect

of methane over the next hundred years will be higher, between 15 and 25% (Lashof and Ahuja, 1990; Rotmans and den Elzen, 1990a). However, latest reviews of the IPCC recommend not to use indirect contributions to GWPs because they are too uncertain (Isaksen *et al.*, 1992).

In this Chapter it is argued that international response with respect to methane does not have to wait until the uncertainties are resolved. This Chapter is structured as follows. Section 7.2 presents the uncertainties in the sources and sinks of methane, as well as how these can be influenced by various feedback mechanisms. Section 7.3 describes the methane model of IMAGE (experimental version 1.6), which simulates the key chemistry processes within the global CH₄-CO-OH cycle. Then section 7.4 evaluates two low IPCC-1990 emission scenarios. In addition a serie of simulation experiments is presented, in which for each experiment the reduction of the methane emissions is determined, necessary to stabilize the atmospheric methane concentration.

7.2 The Science

7.2.1 Sources

Biogenic methane is produced during microbial decomposition of organic material in an anaerobic environment. This process, called methanogenesis, is a very complicated and temperature dependent process. The biogenic methane sources are natural wetlands, wetland rice cultivation, landfills

and deposits of solid waste, animals (enteric fermentation and methane from animal waste), biomass burning, termites, oceans and fresh water systems. Fossil sources and non-biogenic sources are natural gas venting, coal mining and methane hydrate destabilization. Over the last couple of years the budget ranges for methane have been narrowing down due to increasing knowledge on individual sources and atmospheric processes. Table 7.1a contains the latest available data on global methane sources based on Rotmans *et al.* (1992), and IPCC-1992 (Watson *et al.*, 1992) and WMO-1992 (Fung *et al.*, 1991). Two-thirds of the emissions would be caused by anthropogenic activities and 10 to 30% by fossil sources. Since these fossil sources tend to be point

sources, while the biogenic emissions tend to be area sources, these might offer easier options for control. One of the most important fossil sources is the methane release from coal mining. The older and the deeper the seams, the higher the methane content. In the future a shift to deep mining can be expected, increasing the potential methane emissions per unit coal. The latest estimates for global methane emissions from coal mining range from 25 to 47 Tg/yr (Watson *et al.*, 1992). A second important source is the exploration and production of gas and oil (25-42 Tg/yr from gas industry, and 5-30 Tg/yr from oil industry by Watson *et al.* (1992)). In normal production circumstances some gas is vented, especially where no market for gas is nearby. Also during

Table 7.1a: Estimated global sources and sinks of methane (Tg CH₄/yr)

	Rotmans <i>et al.</i> (1992) ^a		WMO-1992 Fung <i>et al.</i> (1991)		IPCC-1992 Watson <i>et al.</i> (1992)	
Sources						
<i>Natural</i>						
Wetlands	115	(100-200)	115	(100-200)	115	(100-200)
Termites	20 ^b	(10-100)	20	(10- 200)	20	(20- 50)
Oceans	10	(5- 20)	10	(5- 20)	10	(5- 20)
Fresh water	5	(1- 25)	-	-	5	(1- 25)
Hydrates	5	(0-100)	-	-	5	(0- 5)
<i>Anthropogenic</i>						
Rice paddies	60	(20-150)	100	(60-170)	60	(20-150)
Enteric fermentation	80	(65-100)	80	(65-100)	80	(65-100)
Fossil fuels	80	(45-100)	75	(50- 95)	100	(70-120)
Biomass burning	55	(20- 80)	55	(50-100)	40	(20- 80)
Landfills	40	(20- 70)	40	(30- 70)	30	(20- 70)
Animal waste	35	n.a.	-	-	25	(20- 30)
Domestic sewage	-	-	-	-	25	?
Other	-	-	5	(0-120)	-	-
Total	505 ^b	(290-965)	500	(380-950)	500 ^c	
Sinks						
Atmospheric removal	470 ^b	(420-520)	450	(405-495)	470	(420-520)
Removal by soils	30	(15- 45)	10	(5- 60)	30	(15- 45)
Atmospheric increase	44	(40- 48)	45	(40- 50)	32	(28- 37)
Total	-	-	505	(450-605)	-	-

^a literature: Watson *et al.* (1990), Watson *et al.* (1992), Van den Born *et al.* (1991), and IPCC (1991).

^b Revised estimate, based on Watson *et al.* (1992) and Fung *et al.* (1991).

^c Watson *et al.* (1992) deduced the total global emissions of CH₄ of about 500 Tg/yr from the magnitude of its sinks and its rate of accumulation in the atmosphere.

Table 7.1b: Anthropogenic methane emissions in the OECD and non-OECD countries (EPA, 1990; Rotmans, 1991).

Source	OECD-countries	non OECD-countries	World
rice paddies	1	59	60
animals	19	61	80
biomass burning	0	55	55
gas production	21	24	45
land fills	21	19	40
coal mining	9	26	35
animal waste	9	26	35
<i>Total anthropogenic</i>	80	270	350

blow-outs a considerable amount of gas can be lost: Rotmans *et al.* (1992) estimate this to be 5-10 Tg/yr extrapolated from data for a number of limited regions (Warriner and Cassity, 1988; Westergaard, 1987; Podio *et al.*, 1983). A third important fossil source is the loss during transportation and distribution of natural gas. This loss is very much dependent on the age and quality of the materials, transport distances and the maintenance level. Emissions by incomplete combustion of liquid fuels in transportation engines, evaporation from asphalt and from coal storage are believed to be minor sources. Rotmans *et al.* (1992) estimated the total CH₄ emissions from these three sources (summarized as fossil fuels in Table 7.1a) at 80 Tg/yr (45-100 Tg/yr).

The most important biogenic sources are natural wetlands and paddy rice fields, which currently contribute about 20% and 12%, respectively to the global methane budget (Watson *et al.*, 1992). Based on a detailed analysis of the available CH₄ emission data from rice paddies, Watson *et al.* revised the IPCC-1990 estimate for the annual CH₄ flux from rice paddies of 100 Tg, to 60 Tg, which is also used by Rotmans *et al.* (1992). While the WMO decided to use the used the IPCC-1990 estimate (Fung *et al.*, 1992). About 15% of the total annual emission of methane is produced by animals through enteric fermentation processes. Landfills are the most important source of methane in the waste disposal sector, but also leakage from biogas digestion, releases from waste water

treatment plants in warm climates and storage of manure and agricultural wastes may be significant. While the overall magnitude of the global methane emissions is reasonably well known, estimates of CH₄ emissions from individual sources are highly uncertain. Most uncertainties arise from lack of field measurements, unknown loss rates or throughput, gaps in our knowledge on the controlling factors of methane fluxes, unknown emission factors and differences in methodologies and input data to measure methane (Rotmans, 1991).

7.2.2 Sinks

Analysis of air contained in ice cores indicates that the methane concentration varied between about 0.35 ppmv and 0.65 ppmv during the period between 160000 and 10000 years ago (Raynaud *et al.*, 1988; Stauffer *et al.*, 1988). Between 2000 and 200 years ago, the atmospheric concentration of methane averaged around 0.8 ppmv (Watson *et al.*, 1990). Since pre-industrial times the atmospheric concentration of methane has more than doubled, resulting in a present-day level of about 1.72 ppmv (Watson *et al.*, 1990; Watson *et al.*, 1992). This is primarily caused by increasing emissions, mainly due to human activities. Another reason for the rapid build-up of methane might be the decreasing rate of oxidation, probably caused by a decreasing availability of hydroxyl (OH) radicals in the atmosphere. Since 1978 the observed rate of increase in atmospheric

methane has been between 14 to 17 ppbv (or about 0.9%) per year (Steele *et al.*, 1987; Blake and Rowland, 1988). Only in the past several years this increase has been slowing down to a rate of 12-13 ppbv per year (Steele *et al.*, 1992). The reasons for the declining growth rate are unknown, indicating significant uncertainties in our understanding of the sources and sinks of methane and their long-term time dependence (Khalil and Rasmussen, 1990a). One hypothesis is that a dramatic decrease in the growth rate of sources in the latitude band between 30-90 °N might account for the slowing down of the atmospheric increase of methane (Thompson *et al.*, 1991).

Methane is removed from the troposphere through a number of processes, of which the photochemical oxidation of methane by hydroxyl radicals in the troposphere is the most important. Soil uptake and transport to the stratosphere are other important sinks of methane, but small in comparison with the oxidation of methane by hydroxyl radicals. Next to the increasing emissions by human activities, another important reason for the rapid build-up of methane might be the decreasing availability of OH radicals. Most model analyses suggest that the global OH concentration has been decreasing since pre-industrial level, although the various modelling estimates vary considerably (Thompson *et al.*, 1991). Most results indi-

cate a decrease of 5-20% since 1900 (Kerr, 1991), but some recent results even indicate that OH levels are actually increasing (Prinn *et al.*, 1991). In spite of lacking evidence the probably decreasing global OH availability might be caused by increasing levels of other trace gases competing with methane. The presence of OH radicals in the troposphere is governed amongst others by such factors as the concentration of ozone, nitrogen oxides and carbon compounds like carbon monoxide, methane and other hydrocarbons. The most important of these trace gases is carbon monoxide, which is, globally averaged, increasing in the troposphere due to direct emissions and as an oxidation product of hydrocarbons (Khalil and Rasmussen, 1988; Seiler *et al.*, 1984; Khalil and Rasmussen, 1990b). This increase, however, is observed only in the northern hemisphere (1% per year), based on sparse observations, while there is no evidence of an increasing trend in the southern hemisphere (Watson *et al.*, 1992). This indicates that the magnitude of the uncertainties in the carbon monoxide is even larger than for methane. In Table 7.2 an estimate is given (IPCC, 1991; Krause *et al.*, 1989). This budget suggests that almost half of the carbon monoxide emissions is anthropogenically influenced. More than one-third is caused by fossil fuel combustion, primarily in the transportation sector and two-thirds would be primarily

Figure 7.1: Methane emissions by regions (IPCC, 1991b)

North America	72.1 Tg/yr
Western Europe	36.6
Eastern OECD	22.7
USSR/Eastern Europe	76.7
Centrally planned Asia	74.2
Middle East	9.3
Africa	65.6
Latin America	64.1
South East Asia	105.2

Total 525.6 Tg/yr

Figure 7.2: Direct anthropogenic carbon monoxide emissions by region (IPCC, 1991b)

North America	71.9 Tg/yr
Western Europe	49.0
Eastern OECD	24.5
USSR/Eastern Europe	50.9
Centrally planned Asia	53.1
Middle East	7.7
Africa	72.2
Latin America	102.5
South East Asia	92.0
Total	523.8 Tg/yr

caused by tropical deforestation and biomass burning. In Figures 7.1 and 7.2 the regional emissions of methane and carbon monoxide are shown as estimated by the IPCC (IPCC, 1991). From Table 7.1b which gives the anthropogenic CH₄ contribution of the OECD and non-OECD countries, it is

evident that the major part of the increasing methane concentrations in the atmosphere can be attributed to the non-OECD countries as opposed to the emissions of carbon dioxide and CFCs.

Table 7.2: Annual Carbon Monoxide Release Rates for Identified Sources (IPCC, 1991b).

Source	Annual release Tg CO (TgC)		Range
Transportation	230	(100)	
Combustion of fossil fuels	60	(25)	
Industrial processes	130	(55)	
Total energy use	420	(180)	350 - 580
Forest clearing	500	(215)	190 - 820
Agriculture	245	(105)	90 - 400
Oxidation man-made hydrocarbon	95	(40)	0 - 190
Total Man-made	1260	(540)	
Plants	130	(55)	50 - 210
Oceans	60	(25)	25 - 95
Forest wild fires	30	(12)	10 - 50
Total Direct	1520	(650)	
Oxidation of natural hydrocarbons	640	(275)	115 - 1170
Oxidation of methane	610	(260)	175 - 1050
Total Natural	1470	(630)	
Total	2730	(1170)	1000 - 4550

7.2.3 Feedbacks

Various climate feedback mechanisms can amplify or damp the methane emissions. Negative feedbacks are related to climate-tropospheric chemistry interactions. A warmer world with a higher absolute humidity implies more OH, and therefore enlarges the atmospheric sink for methane. In addition, higher global temperatures will influence the reaction rate of hydroxyl radicals with methane, leading to enhanced destruction of methane by hydroxyl radicals.

A positive as well as a negative feedback may occur through the production of another greenhouse gas, tropospheric ozone, due to increased atmospheric methane.

The positive feedback is related to the role of tropospheric ozone as a greenhouse gas. The negative feedback concerns methane concentrations since tropospheric ozone has a positive influence on hydroxyl production. Various positive feedbacks are associated with increasing microbial activity and biological productivity if global temperature increases. These include increased fluxes of methane from soils, natural wetlands, rice paddies and the oceans (Khalil and Rasmussen, 1989).

Another important potential feedback is the destabilisation of methane hydrates in ocean sediments and permafrost accompanying global temperature increase. Methane release from hydrates is thought to be a large potential source of methane emission, but the long time scales for warming the methane hydrates, uncertainties in distribution and total volume of hydrates, and velocity of heat diffusion through different sediments make it difficult to estimate present and future contribution of hydrates to global warming (Kvenvolden, 1988; MacDonald, 1990). According to current scientific opinion the positive feedbacks largely dominate the negative feedbacks (Watson *et al.*, 1990). Because of their current uncertainties quantifying the magnitudes of these feedbacks is very difficult. This study only considers some of these feedbacks which can be quantified in a global way comparatively easy.

7.3 Methodology

To assess the role of methane within the global CH₄-CO-OH cycle a methane model is developed for the overall modelling framework IMAGE (experimental version 1.6), which is a submodel of the atmospheric chemistry model. This tropospheric chemical methane model simulates comprehensively key processes of the global CH₄-CO-OH cycle (Rotmans *et al.*, 1992; Rotmans *et al.*, 1990). This model is a box model that produces globally averaged atmospheric concentrations of methane, carbon monoxide and hydroxyl, taking into account the heterogeneity of the chemical and transport processes by using suitably globally averaged descriptions of these processes. This simple approach is basically an interpretation of the one-, two- and three-dimensional photochemical models simulating the CH₄-CO-OH cycle (Bruhl and Crutzen, 1988; Thompson and Cicerone, 1986; Isaksen and Hov, 1987). All these models have structural limitations and contain a number of imprecisions. One of the major uncertainties arises from imprecision of photochemical reaction rates. The integration of processes that take place on totally different time and length scales is another major problem.

Although the methane box model is an oversimplification of complex reality, it can be used to gain more insight into the driving forces of the CH₄-CO-OH cycle as well as to present estimates of possible future changes in chemical composition and temperatures of the atmosphere. As opposed to previous models it includes an extensive investigation of the sources of methane and carbon monoxide, leading to future emissions scenarios based on social and economic trends. In the model the individual sources of methane are specified: anthropogenic (rice paddies, cattle, biomass burning, fossil fuel usage, landfills and leakage of natural gas as well as natural (termites, wetlands and oceans). The magnitude of the natural sources is kept constant, although in the future large areas of natural wetlands may be affected by land reclamation, or new wetlands may be created by the realization of hydro-electric power schemes (Amazonian

Figure 7.3: Systems diagram of the methane model

wetlands). The globally averaged tropospheric concentration of methane is determined by the emissions of methane and the removal of methane by the uptake of soils, transport to the stratosphere and oxidation. Both the soil uptake rate and stratospheric transport velocity are assumed to be constant, whereas the oxidation rate is proportional to the tropospheric hydroxyl concentration. As to carbon monoxide three sources are considered: direct emissions, emissions by oxidation of non-methane hydrocarbons

(NMHC), and emissions by oxidation of methane. Concerning the direct emissions and the oxidation by NMHC this study distinguish natural, fossil fuel related and other anthropogenic sources. While constant figures were taken for natural emissions, for anthropogenic but non-fossil fuel related emissions growth is assumed proportional to population. Sources treated this way are emissions from deforestation, agricultural practices like savanna burning, solvent use, as well as residential combustion of fossil

fuel. The major removal mechanisms in the model are the oxidation by hydroxyl radicals and the uptake by soils. The concentration of hydroxyl is determined by balancing the production of hydroxyl and its loss. The latter is predominantly determined by the reaction of hydroxyl with methane and carbon monoxide (Rotmans, 1990).

The evolution of oxidizing compounds is described in the way suggested by the NASA workshop of Prather *et al.* (1988). The production of hydroxyl is dependent on the concentration of nitrogen oxides, tropospheric ozone, water vapour and of the total column ozone. Changes in tropospheric ozone are dependent on the changes in the concentrations of methane, carbon monoxide, nitrogen oxides and the total column ozone. The rate coefficients are calculated taking global averages of local rates (Prather and Spivakovsky, 1990; Vagjani and Ravishankara, 1991). The coefficients quantifying the dependencies are calculated using coefficients for coherent regions of Thompson *et al.* (1989), by taking weighted global averages of local trends in emissions

(Bruhl and Crutzen, 1988). The total column ozone in its turn, is parameterized by the concentration of stratospheric chloride; the relation is linear for chloride concentrations exceeding a threshold level. The coefficients in the parameterization of the column ozone are found by fitting model results to the TOMS data (Stolarski *et al.*, 1991). In Figure 7.3 the methane module is presented schematically.

The simulation time of the model is 200 years, from the year 1900 till 2100. The initial atmospheric concentration of methane (in 1900) is 0.90 ppmv. Simulated present-day (1990) levels for methane, carbon monoxide and hydroxyl are 1.72 ppmv, 0.11 ppmv, and $5.3 \cdot 10^{-8}$ ppmv, respectively. Calibration of the simulated methane concentrations with the estimated trend for the period 1900 till 1990, (Figure 7.4a) and the observed values from 1970 till 1990 (Figure 7.4b), yields a fairly good fitting curve, although the model does not entirely show the decline in CH₄ growth rate from 1970 to 1990. Hydroxyl concentrations show a decrease by 8% since 1900, which is within

Figure 7.4a: Simulated and observed CH₄-concentration over the period 1900-1990

Figure 7.4b: Simulated and observed CH₄-concentration over the period 1962-1990

the uncertainty range presented in literature (Kerr, 1991). Current simulated carbon monoxide value is slightly higher than the observed 1990 value, but the simulated pattern is similar to the observed trend (Khalil and Rasmussen, 1988).

As a kind of sensitivity study this study considers some of the climate related feedback mechanisms related to increased microbial activity in natural wetlands and rice paddies, the feedback caused by destabilisation of methane hydrates in ocean sediments and the feedback involving tropospheric ozone. The additional release of methane by both wetlands and rice paddies is modelled by parameterizing the relationship between methanogenesis and temperature by a Q_{10} -value that reflects the rate of increase of methanogenesis as global temperature rises 10°C. For wetland and rice paddies, having an identical methanogenesis process, equal Q_{10} -values are chosen, varying between 1.5 and 2.5, based on laboratory and field experiments (Khalil and Rasmussen, 1991). Under the assumption of uniformly distributed methane hydrates in ocean floor sediments, the increase of hydrate stability is calculated as an exponential function of the ocean temperature increase at the same depth. Subsequently the resulting methane emissions are calculated as a linear function of the increased hydrate stability depth, concentration of methane within the hydrate stability zone, the average thickness of this zone and the averaged velocity of heat diffusion through hydrate containing sediment (den Elzen and Rotmans, 1993). Although this modelling approach is simple and does not pretend to give a comprehensive picture of all climate related feedbacks within the methane cycle, it may give an indication about the potential magnitude of some of the feedbacks.

7.4 Results

From a policy viewpoint it is interesting to assess the possibilities of stabilizing the concentrations of methane in the atmosphere. In order to assess the order of magnitude of the emission controls necessary to stabilize

or reduce methane concentrations in the atmosphere a number of global emissions scenarios are analysed. Two low emissions scenarios for methane, carbon monoxide, non-methane hydrocarbons and NO_x are evaluated here. In addition a sensitivity analysis is performed with varying assumptions concerning the emissions of the above-mentioned gases. The figures of the emissions scenarios for CH₄, CO and NO_x are presented in *Table 7.3*, while the resulting concentrations of CH₄, CO and OH are presented in *Table 7.4*. The first case is the IPCC-1990 Control Policies scenario, and the second case, the IPCC-1990 Accelerated Policies scenario, as described in IPCC (1991b). The main difference between these two scenarios primarily relates to the emissions of carbon dioxide, and, to a lesser degree, to the emissions of methane and carbon monoxide (*Table 7.3*). Both scenarios are calculated with and without methane feedbacks to assess the impact of the various feedbacks built into IMAGE (experimental version 1.6) on emission controls necessary to stabilize concentrations if these feedbacks would materialize. The results of the IPCC-1990 Control Policies scenario indicate, that a reduction of direct carbon monoxide emissions by 20% in 2000 and 35% in 2025 combined with a moderate increase of 15% of the global methane emissions by 2025 would reverse the increasing trend of the methane concentrations at a level of around 2090 ppbv around 2060 as compared with 1713 ppbv at present and about 900 ppbv in 1900. Around the turn of the century the increase of the methane concentrations would be reduced from about 0.7-0.9% (currently) to 0.15% annually.

In the IPCC-1990 Accelerated Policies scenario an increase of the global methane emissions by 10% in 2025 accompanied by a similar pattern for the direct carbon monoxide emissions as in the IPCC-1990 Control Policies scenario, would reverse the increase of atmospheric methane at a level somewhat lower than in the IPCC-1990 Control Policies scenario, namely at about 1825 ppbv.

The next two runs of *Table 7.3* and *7.4*

show that, if the temperature induced biogeochemical feedbacks on the emissions of methane do materialize, the above mentioned controls are not sufficient. The results for the IPCC-1990 Control Policies scenario show that methane concentrations might result to be about 25% higher by 2100 if these feedbacks would materialize. In *Figures 7.5 and 7.6* the resulting methane concentrations for the IPCC-1990 Control Policies and Accelerated Policies scenarios are depicted, with and without biospheric feedbacks. The uncertainty ranges presented are the result of an analysis based on model comparisons by Guthrie and Yarwood (1991).

Additional runs have been made varying the emissions of methane, carbon monoxide, CFCs and HCFCs and nitrogen oxides. These experiments are variations on the IPCC-1990 Control Policies scenario, and are represented in runs 5 till 10 in *Table 7.3 and 7.4*.

Run 5 shows that if the direct emissions of carbon monoxide increase by 20%, the methane emissions have to be reduced by 15% in 2025 and almost 30% (27%) in 2100, in order to stabilize atmospheric methane at a level of 1800 ppbv.

In run 6 the direct emissions of carbon monoxide remain unchanged from the year 2000. Then a stabilization of the atmospheric methane concentrations at present-day levels requires a 8% reduction in 2100 of the methane emissions.

Lashof and Tirpack (1989) suggest that a 10-20% reduction of methane emissions combined with stabilizing CO₂-emissions would stabilize methane concentrations at current levels. To verify this statement in run 7 methane emissions have been decreased by 20% between 1990 and 2050 while direct carbon monoxide emissions were held fixed. This results in a stabilization of the atmospheric methane concentrations at 1600 ppbv. Total CO₂-emissions also stabilize at a level slightly below present-day values. This corresponds well with the values presented by Lashof and Tirpack (1989).

Run 8 shows the impact of a more strict CFC and HCFC policy. The IPCC-1990 Control Policies scenario is used in combination with a phase out of CFCs by 2000, no substitution of CFCs by HCFCs and a phase out of HCFCs between 2020 and 2040 (WMO reference scenario) (WMO, 1992). The stricter policy on CFCs and HCFCs induces a more rapid recovery of the stratospheric ozone layer which results in a decreased production of hydroxyl in the troposphere. A reduction by 3% in 2100 of the methane emissions is required for stabilizing methane concentrations at present-day levels.

Run 9 shows the strong influence of nitrogen oxides on the composition of the atmosphere. The IPCC-1990 Control Policies scenario has been combined with the nitrogen oxides emissions from the IPCC-

Figure 7.5: Atmospheric concentrations of methane for the IPCC 1990 Control Policies scenario with and without feed-backs.

(shaded area denotes the range of simulated values found by Guthrie and Yarwood (1991))

— with feedbacks
- - - without feedbacks

Figure 7.6: Atmospheric concentrations of methane for the IPCC-1990 Accelerated Policies scenario with and without feedbacks.

(shaded area denotes the range of simulated values found by Guthrie and Yarwood (1991))

1990 Accelerated Policies scenario, which are higher! Due to the higher levels of nitrogen oxides the oxidizing capacity of the atmosphere increases. This allows the methane emissions to increase by 10% before 2100 in order to stabilize the methane concentrations.

The last run is a reference run using a variant of the IPCC-1990 Control Policies scenario that aims at stabilization of atmospheric methane at present-day level. In this case a 5% increase by 2100 is permitted in order to achieve the target set.

Comparing runs 8 and 9 with the reference run (10) shows us that the adverse effect of a stricter CFC and HCFC policies on methane levels requires an extra 8% reduction of methane emissions by 2100 to achieve a similar stabilization pattern.

Furthermore it is shown that even a relatively small difference between the nitrogen oxides scenarios of IPCC-1990 Control Policies and IPCC-1990 Accelerated Policies results in a substantial effect on atmospheric methane: compared to the reference case (run 10) an extra reduction of methane emissions of about 7% by 2100 is required to stabilize atmospheric methane at present-day level. This illustrates the sensitivity of the atmospheric composition to emissions and chemistry of nitrogen oxides, chloride precursors and ozone. Moreover it illustrates that the control of methane concentrations interferes with the control of

acid decompositions and ozone depleting compounds.

From the calculations presented above it can be derived that the following strategies would lead to the reversal of the increasing trend of the methane concentrations below 2000 ppbv in the atmosphere:

- an increase of methane emissions limited to 10-15% above present levels combined with a 35% reduction of carbon monoxide emissions by 2025 (the IPCC-1990 Control Policies and Accelerated Policies scenarios) (run 1 and 2);

To meet the requirements of not only reversing the increasing trend, but also stabilize the atmospheric methane concentrations around present-day levels the following strategies can be adopted:

- a decrease of methane emissions by 15% by 2025 and about 30% by 2100, combined with a growth of direct carbon monoxide emissions limited to 6% only above present levels by 2025 and (run 5);
- a decrease of methane emissions by 12% by 2025 and 20% by 2050 combined with a stabilization of direct carbon monoxide emissions (run 7);
- a stabilization of methane emissions by 2025 and reduction by about 10% by 2100, combined with a 20% reduction of the carbon monoxide emissions by

2000, and stabilization at this 20% lower level afterwards (run 6):

- an increase of methane emissions by 8% by 2025 and 5% by 2100, combined with a 35% reduction of carbon monoxide emissions by 2025 (run 10: variant on the IPCC-1990 Control Policies scenario).

Furthermore it should be noted that if controls on either acid deposition or ozone depleting compounds were tightened extra reduction of methane emissions should be required.

The control options for the emissions of methane and carbon monoxide are described in Rotmans *et al.* (1992).

The exact reduction requirement very much depends on the controls on other atmospheric constituents which play a role in the methane oxidation process, especially carbon monoxide as well as nitrogen oxides and ozone depleting compounds. It should be realized, however, that controls of nitrogen oxides and CFCs aim at entirely different goals. If temperature related biospheric feedbacks would induce additional methane emissions the gains from the above-mentioned global emission reduction could be offset.

7.5 Conclusions

This study clearly shows that our knowledge of the sources and sinks of methane is deficient. What we do know, however, is that the atmospheric concentration of methane has more than doubled since pre-industrial times and is now substantially higher than in the past 160,000 years. We also know that increasing man-made emissions of methane are the primary cause of this rapid increase. Not only because its potential impact on climate change, but also because its direct effect on tropospheric air quality further increasing methane concentrations could possibly threaten the environment and human health. In order to minimize this risk atmospheric methane concentrations should be stabilized at present day levels as soon as possible. In order to stabilize atmospheric methane concentrations we do not need to know precisely the individual emissions from each anthropogenic source nor the exact changing pattern of the sources and sinks in time. We only need to know by which amount emissions exceed atmospheric removal and how the emissions can be reduced. The extent to which methane emissions exceed atmospheric methane removal can be estimated from observations. An adequate level of emissions reductions can be achieved from some combination of sources. Global emission reductions up to 20% are likely to stabilize concentrations.

Table 7.3: Sets of scenarios for controlling atmospheric methane concentrations

CO [CH₄] denotes CO emissions by CH₄ oxidation
 CO [NMHC] denotes CO emissions by NMHC oxidation
 CO [direct] denotes direct CO emissions

Run 1: IPCC-1990 Control Policies scenario without feedbacks

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (Tg/yr)	525	541	557	567	577	587	597	607	622	561	504
CO [CH ₄] (Tg/yr)	586	654	713	725	730	738	746	755	772	749	710
CO [NMHC] (Tg/yr)	650	638	625	628	631	634	637	640	652	658	660
CO [direct] (Tg/yr)	1260	1128	996	954	911	869	826	784	670	663	656
NO _x (TgN/yr)	50.2	50.3	50.3	49.5	48.7	48.0	47.2	46.4	41.9	39.3	39.4

Run 2: IPCC-1990 Accelerated Policies scenario without feedbacks

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (Tg/yr)	525	545	565	569	572	577	579	583	552	529	501
CO [CH ₄] (Tg/yr)	585	658	724	735	740	746	752	755	727	719	694
CO [NMHC] (Tg/yr)	650	638	625	628	631	634	637	640	652	658	660
CO [direct] (Tg/yr)	1260	1110	959	926	894	861	829	796	733	670	656
NO _x (TgN/yr)	50.2	50.7	50.5	50.4	50.3	50.1	50.0	49.9	43.8	42.9	43.5

Run 3: IPCC-1990 Control Policies scenario with feedbacks

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (Tg/yr)	525	539	559	572	585	597	610	624	654	610	564
CO [CH ₄] (Tg/yr)	588	652	709	721	727	735	745	755	785	778	759
CO [NMHC] (Tg/yr)	650	638	625	628	631	634	637	640	652	658	660
CO [direct] (Tg/yr)	1260	1128	996	954	911	869	826	784	670	663	656
NO _x (TgN/yr)	50.2	50.3	50.3	49.5	48.7	48.0	47.2	46.4	41.9	39.3	39.4

Run 4: IPCC-1990 Accelerated Policies scenario with feedbacks

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (Tg/yr)	525	543	567	573	579	586	592	598	580	568	548
CO [CH ₄] (Tg/yr)	587	656	721	731	736	743	750	756	738	744	732
CO [NMHC] (Tg/yr)	650	638	625	628	631	634	637	640	652	658	660
CO [direct] (Tg/yr)	1260	1110	959	926	894	861	829	796	733	670	656
NO _x (TgN/yr)	50.2	50.7	50.5	50.4	50.3	50.1	50.0	49.9	43.8	42.9	43.5

Run 5: IPCC-1990 Control Policies scenario with direct CO emissions increased by 20% by 2100
CH₄ emissions chosen to stabilize CH₄ concentrations at the 1990 level

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (Tg/yr)	525	510	495	486	477	468	459	450	415	400	385
CO [CH ₄] (Tg/yr)	586	615	631	625	612	600	588	576	523	495	482
CO [NMHC] (Tg/yr)	650	638	625	628	631	634	637	640	652	658	660
CO [direct] (Tg/yr)	1260	1271	1283	1294	1306	1317	1329	1340	1397	1455	1512
NO _x (TgN/yr)	50.2	50.3	50.3	49.5	48.7	48.0	47.2	46.4	41.9	39.3	39.4

Run 6: IPCC-1990 Control Policies scenario with direct CO emissions constant after 2000
CH₄ emissions chosen to stabilize CH₄ concentrations at the 1990 level

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (Tg/yr)	525	525	525	525	525	525	525	525	495	488	480
CO [CH ₄] (Tg/yr)	586	652	706	700	688	679	671	665	632	618	617
CO [NMHC] (Tg/yr)	650	638	625	628	631	634	637	640	652	658	660
CO [direct] (Tg/yr)	1260	1128	996	996	996	996	996	996	996	996	996
NO _x (TgN/yr)	50.2	50.3	50.3	49.5	48.7	48.0	47.2	46.4	41.9	39.3	39.4

Run 7: IPCC-1990 Control Policies scenario with direct CO emissions constant after 2000
CH₄ emissions reduced by 20% between 1990 and 2050

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (Tg/yr)	525	516	508	499	490	481	473	464	420	420	420
CO [CH ₄] (Tg/yr)	586	619	639	637	628	619	610	600	550	528	531
CO [NMHC] (Tg/yr)	650	638	625	628	631	634	637	640	652	658	660
CO [direct] (Tg/yr)	1260	1260	1260	1260	1260	1260	1260	1260	1260	1260	1260
NO _x (TgN/yr)	50.2	50.3	50.3	49.5	48.7	48.0	47.2	46.4	41.9	39.3	39.4

Run 8: IPCC-1990 Control Policies scenario with no substitution of CFCs by HCFCs
HCFCs phased out between 2020 and 2040
CH₄ emissions chosen to stabilize CH₄ concentrations at the 1990 level

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (Tg/yr)	525	533	540	544	548	552	556	560	540	525	510
CO [CH ₄] (Tg/yr)	586	653	708	716	716	719	722	725	697	664	666
CO [NMHC] (Tg/yr)	650	638	625	628	631	634	637	640	652	658	660
CO [direct] (Tg/yr)	1260	1128	996	954	911	869	826	784	670	663	656
NO _x (TgN/yr)	50.2	50.3	50.3	49.5	48.7	48.0	47.2	46.4	41.9	39.3	39.4

Run 9: IPCC-1990 Control Policies scenario with NO_x emissions as in the IPCC-1990
Accelerated Policies scenario
CH₄ emissions chosen to stabilize CH₄ concentrations at the 1990 level

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (Tg/yr)	525	532	540	547	554	561	568	575	575	577	580
CO [CH ₄] (Tg/yr)	585	652	710	721	727	735	743	749	744	745	753
CO [NMHC] (Tg/yr)	650	638	625	628	631	634	637	640	652	658	660
CO [direct] (Tg/yr)	1260	1128	996	954	911	869	826	784	670	663	656
NO _x (TgN/yr)	50.2	50.7	50.5	50.4	50.3	50.1	50.0	49.9	43.8	42.9	43.5

Reference run: IPCC-1990 Control Policies scenario
CH₄ emissions chosen to stabilize CH₄ concentrations at the 1990 level

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (Tg/yr)	525	533	540	545	550	555	560	565	563	558	553
CO [CH ₄] (Tg/yr)	586	653	709	717	719	722	726	731	728	715	718
CO [NMHC] (Tg/yr)	650	638	625	628	631	634	637	640	652	658	660
CO [direct] (Tg/yr)	1260	1128	996	954	911	869	826	784	670	663	656
NO _x (TgN/yr)	50.2	50.3	50.3	49.5	48.7	48.0	47.2	46.4	41.9	39.3	39.4

Table 7.4: Concentrations of methane, carbon monoxide, hydroxyl for the different sets of scenarios

Run 1: IPCC-1990 Control Policies scenario without feedbacks

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (ppbv)	1716	1798	1822	1822	1831	1849	1874	1905	2070	2000	1657
CO (ppbv)	114	105	95	93	91	90	89	88	89	87	76
OH (pptv)	0.053	0.056	0.060	0.062	0.062	0.062	0.062	0.061	0.058	0.058	0.066

Run 2: IPCC-1990 Accelerated Policies scenario without feedbacks

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (ppbv)	1716	1800	1824	1819	1813	1805	1796	1787	1714	1540	1292
CO (ppbv)	114	104	93	91	89	87	85	83	80	71	62
OH (pptv)	0.053	0.057	0.061	0.062	0.063	0.065	0.065	0.065	0.056	0.072	0.083

Run 3: IPCC-1990 Control Policies scenario with feedbacks

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (ppbv)	1716	1798	1822	1824	1843	1873	1914	1962	2243	2317	2100
CO (ppbv)	114	105	95	93	91	90	90	90	94	97	90
OH (pptv)	0.053	0.056	0.061	0.061	0.061	0.061	0.061	0.060	0.055	0.052	0.056

Run 4: IPCC-1990 Accelerated Policies scenario with feedbacks

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (ppbv)	1716	1800	1824	1821	1824	1828	1833	1841	1865	1786	1607
CO (ppbv)	114	104	93	91	90	88	86	85	85	79	72
OH (pptv)	0.053	0.057	0.061	0.062	0.063	0.063	0.064	0.064	0.062	0.065	0.071

Run 5: IPCC-1990 Control Policies scenario with direct CO emissions increased by 20% by 2100
CH₄ emissions chosen to stabilize CH₄ concentration at the 1990 level

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (ppbv)	1716	1794	1810	1799	1786	1773	1760	1747	1711	1714	1712
CO (ppbv)	114	115	114	115	116	118	119	120	129	137	143
OH (pptv)	0.053	0.056	0.054	0.054	0.053	0.052	0.052	0.051	0.057	0.045	0.044

Run 6: IPCC-1990 Control Policies scenario with direct CO emissions constant after 2000
CH₄ emissions chosen to stabilize CH₄ concentrations at the 1990 level

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (ppbv)	1716	1785	1771	1727	1699	1685	1684	1691	1715	1722	1710
CO (ppbv)	114	105	94	92	91	92	92	93	98	100	99
OH (pptv)	0.053	0.056	0.062	0.063	0.063	0.062	0.062	0.061	0.057	0.055	0.056

Run 7: IPCC-1990 Control Policies scenario with direct CO emissions constant after 2000
CH₄ emissions reduced by 20% between 1990 and 2050

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (ppbv)	1716	1797	1823	1821	1812	1799	1783	1764	1647	1598	1607
CO (ppbv)	114	114	113	113	114	114	115	115	115	115	115
OH (pptv)	0.053	0.053	0.054	0.054	0.053	0.053	0.053	0.053	0.052	0.051	0.051

Run 8: IPCC-1990 Control Policies scenario with no substitution of CFCs by HCFCs
HCFCs phased out between 2020 and 2040
CH₄ emissions chosen to stabilize CH₄ concentrations at the 1990 level

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (ppbv)	1716	1797	1823	1821	1812	1799	1783	1764	1647	1598	1607
CO (ppbv)	114	105	94	91	88	86	84	82	78	82	81
OH (pptv)	0.053	0.056	0.061	0.063	0.063	0.064	0.065	0.065	0.064	0.060	0.060

Run 9: IPCC-1990 Control Policies scenario with NO_x emissions as in the IPCC-1990 Accelerated
Policies scenario
CH₄ emissions chosen to stabilize CH₄ concentrations at the 1990 level

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (ppbv)	1716	1797	1823	1821	1812	1799	1783	1764	1647	1598	1607
CO (ppbv)	114	105	94	90	87	85	82	80	76	76	75
OH (pptv)	0.053	0.056	0.061	0.062	0.064	0.066	0.067	0.068	0.068	0.068	0.069

Reference run: IPCC-1990 Control Policies scenario
CH₄ emissions chosen to stabilize CH₄ concentrations at the 1990 level

	1990	1995	2000	2005	2010	2015	2020	2025	2050	2075	2100
CH ₄ (ppbv)	1716	1797	1823	1821	1812	1799	1783	1764	1647	1598	1607
CO (ppbv)	114	105	94	91	88	86	84	82	77	78	78
OH (pptv)	0.053	0.056	0.061	0.063	0.064	0.064	0.065	0.066	0.066	0.064	0.065

8

An uncertainty and sensitivity analysis of IMAGE

8.1 Introduction

The IMAGE model (experimental version 1.6) is designed to represent the 'state-of-the-art' scientific knowledge in a dynamic, integrated manner, whereby estimates of present-day uncertainties about global climate change and ozone depletion are included, in a single framework. One of the objectives when developing of an integrated model is to acquire insight into the composite uncertainty in the final model results which is due to the sequence of individual uncertainties.

This Chapter presents an uncertainty and a sensitivity analysis of IMAGE (experimental version 1.6), which is meant to quantitatively describe and analyse the total uncertainty in the model outcomes, as well detecting and identifying the origins of the uncertainty associated with the model. For the purposes of this study, sensitivity and uncertainty analysis are defined as follows (Janssen *et al.*, 1990):

- (i) *sensitivity analysis*: the study of the influence of variations in model parameters, initial conditions etc. on model outputs, whereby the probability of the occurrence of such variations is not considered.
- (ii) *uncertainty analysis*: the study of the uncertain aspects of a model, and of their influence on the (uncertainty of the) model outputs. The probability of the occurrence of variations in these 'uncertainty' or 'sensitivity' sources forms the central theme.

Iman and Helton (1988) and Janssen *et al.* (1990) survey of methods and techniques for the performance of sensitivity and uncertainty analyses are given.

In the past, various sensitivity analysis techniques have been used to evaluate a number of IMAGE (version 1.0) modules:

1. the technique of metamodeling and experimental designs (Kleijnen, 1987) was used in studies by Rotmans and Vrieze (1990), van Ham *et al.* (1990) and Kleijnen *et al.* (1992) to derive relationships between input and output variables of a model (regression models). The use of experimental designs leads to a systematic way of varying the model parameters, and thus to an efficient and effective performance of the model experiments. In Rotmans and Vrieze (1990) this technique has been applied to the sea level rise model, and in van Ham *et al.* (1990) and Kleijnen *et al.* (1992) to the socio-economic model, and separately, to the ocean module and to the terrestrial biota module of the carbon cycle.

2. sequential bifurcation screening. This technique of sensitivity analysis is an efficient screening technique which enables the user to identify the important elements in the large set of model parameters. This technique was applied to the entire carbon cycle model (Bettonvil, 1991; Bettonvil and Kleijnen, 1990).

Hitherto, only one preliminary uncertainty analysis has been performed on the atmospheric chemistry model of IMAGE (version 2.0) (Krol and van der Woerd, 1994), using the software package UNCSAM (UNCertainty analysis by Monte Carlo SAMpling techniques). This package was specially developed at RIVM for performing sensitivity and uncertainty analysis on a wide range of mathematical models by means of Monte Carlo sampling. The package uses Monte Carlo-based methods in conjunction with regression and correlation analysis to analyse the models' sensitivities and uncertainties (Janssen *et al.*, 1992a; 1992b).

This Chapter presents an uncertainty and sensitivity analysis of the IMAGE (experimental version 1.6) carbon cycle model and

the halocarbon model, as well as such an analysis of the entire IMAGE model. As in the previous sensitivity studies conducted on IMAGE, the only uncertainty sources considered here are a set of selected model parameters. This analysis focuses on the calculation and evaluation of: (i) *the total uncertainty in the model outcome due to the uncertainties in the selected model parameters* (ii) *the contribution of the individual model parameters and interacting model parameters to the total uncertainty*. For this purpose UNCSAM is used. However, since UNCSAM makes use of linear regression techniques, the contribution of interacting model parameters to the total uncertainty cannot be adequately determined in situations where a linear regression models renders an inadequate fit. Therefore, in the analysis of the carbon cycle model, where interacting model parameters are expected to contribute significantly to the total uncertainty (see van Ham *et al.*, 1990), a more advanced regression model was applied, using the technique of metamodelling (Kleijnen, 1987). However, metamodelling has here been used in a manner somewhat different from that originally employed, since instead of varying the model parameters in a systematic way using experimental designs, the values of the selected parameters are determined by means of Monte Carlo sampling using UNCSAM.

The structure of this Chapter is as follows. Section 8.2 describes the general set up for the sensitivity and uncertainty analysis, and moreover presents the methodology of Monte Carlo-based methods, metamodelling (Kleijnen, 1987), and metamodelling in combination with Monte Carlo sampling. Sections 8.3 and 8.4 present a sensitivity and uncertainty analysis of the carbon cycle model and the halocarbon model. In section 8.5, an uncertainty analysis for the IMAGE model (experimental version 1.6) as a whole is given, whereby only the total uncertainty in the model outcomes, radiative forcing and global mean temperature increase, are presented. Finally, conclusions are drawn in section 8.6.

8.2 Methodology

8.2.1 Introduction

In Janssen *et al.* (1992b) a general strategy for performing a sensitivity and uncertainty analysis is described in various steps:

1. *problem formulation*
2. *inventory of the uncertainty or sensitivity sources* (Here a group of model parameters which characterize the behaviour of the main modelled processes is selected).
3. *Quantification of the sources*
 - a. For the purpose of sensitivity analysis this involves a specification of the nominal values of the model parameters and the appropriate variations around these values.
 - b. For the purpose of uncertainty analysis, the uncertainty in the model parameters is usually described by specifying their probability distributions (e.g. by giving the mean, standard deviation, minimum, maximum, and distribution type), and their mutual correlations.
4. *Evaluation of the effects on the model outputs*
 - a. In a sensitivity analysis the influence of the variations of the various sources around their nominal values is evaluated, and reported in a tabular or graphical form. Furthermore, the ranking in the relative importance of these sources is given.
 - b. In an uncertainty analysis, the total influence of the uncertainties in the various sources on the model outcomes is evaluated, and reported by presenting the range of model outputs, the mean and variance, empirical distribution functions, scatter diagrams, and percentile values. To specify the accuracy of these estimates the confidence bounds are also presented. In addition, the individual contribution of each source to the total uncertainty is given, using a correlation or regression analysis.
5. *Performing a robustness study on the results*

Finally, the robustness of the results is checked with respect to choices and specifications of the various sources.

8.2.2 Monte Carlo-based methods

Monte Carlo-based methods rely on the assumption that variations, or, as the case may be, uncertainties in the sources can be suitably described by specifying probability distributions and mutual correlations. After the specification of these distributions, sampling is performed either using random sampling or the more advanced and efficient Latin Hypercube sampling (LHS) technique (McKay *et al.*, 1979; Iman and Conover, 1980). The resulting set of sampled values for the various sources (Monte Carlo sampling) are subsequently used to simulate the model outputs (Monte Carlo simulation) associated with these sources, and the total uncertainty, as well as the various contributions to this uncertainty. The analysis consists of the calculation of basic statistical information (means, variances, percentiles, histograms, etc.), an evaluation of the confidence bounds to assess the accuracy of these quantities, and finally, a regression and correlation analysis to calculate sensitivity contribution of the individual sources and their respective contributions to uncertainty (Janssen *et al.*, 1992a).

The above mentioned analysis is implemented using the UNCSAM software package. The statistics and the measures for the regression analysis incorporated in UNCSAM will therefore now be briefly described (Janssen *et al.*, 1992a; 1992b):

Suppose that the model is seen as a mathematical function $f()$ between an output variable y , and the p chosen model parameters.

$$y = f(z_1, \dots, z_p) \quad (8.1)$$

This function can be approximated by the linear regression model:

$$y^* = \hat{\gamma}_0 + \sum_{i=1}^p \hat{\gamma}_i z_i =: y + \hat{e} \quad (8.2)$$

where $\hat{\gamma}_0, \dots, \hat{\gamma}_p$ are the estimated regression coefficients using the ordinary least square method (OLS) (referred to as *ordinary regression coefficients*) and $\hat{e}$ the regression residual.

Therefore, a number L ($L > p$) of sampled 'sources' ($z_{1k}, \dots, z_{pk}$) ($k=1, \dots, L$) are chosen, and N simulation runs are performed with the model. Let $y^T = (y_1, \dots, y_L)^T$ denotes the vector of the simulated model outcome, where y_k denotes the model output in run k ($k=1, \dots, L$).

The validity of linear regression model y^* to approximate the original output y is measured using the *coefficient-of-determination* (COD or R^2):

$$R^2 = \frac{S_{y^*}^2}{S_y^2} \quad (8.3)$$

where S^2 is the sample variance of the associated quantity. R^2 is a number between 0 and 1, where $R^2 \sim 1$ indicates a good approximation.

Evaluation of sensitivity and uncertainty contributions

$\hat{\gamma}_i$, $i=1, \dots, p$ can be considered as an *absolute sensitivity measure*, since it measures the absolute change Δy of y if z_i changes by an amount Δz_i , while the other sources remain constant (Janssen *et al.*, 1990): $\Delta y = \hat{\gamma}_i \Delta z_i$. This measure generates a global or local indication of the sensitivity, depending on the scale on which the regression model is valid (Janssen *et al.*, 1992a).

Janssen *et al.* (1990) proposed various measures for expressing the uncertainty contribution of the sources z_i to the model outcome y . The measures *Standardized Regression Coefficient* (SRC) and the *Relative Partial Sum-of-Squares* (RPSS), both used in the analyses (section 8.3), are adequate when the sources show no substantial correlation, and if the linear regression model is a fair approximation of the original model output y (i.e. $R^2 \sim 1$). These measures are defined as follows:

- The measure SRC can be considered to be a *relative uncertainty measure*, and expresses the relative change Δy of y with respect to its standard deviation, if z_i changes by an amount Δz_i with respect to its standard deviation, while the other sources remain constant:

$$SRC_i = \hat{\gamma}_i \frac{S_{z_i}}{S_y} \quad i=1, \dots, p \quad (8.4)$$

where S_y^2 is the sample variance of $y_1, \dots, y_N$.

The measure *RPSS* describes the loss of the ‘fit’ (i.e. the decline in the relative explained variance (*R*²)), if the source *z_i* is removed from the equation, and is defined as:

$$RPSS_i = \frac{S_{\hat{e}|i}^2 - S_{\hat{e}}^2}{S_y^2} \tag{8.5}$$

where *S_e²* = the sample variance of the residuals *e* of the ‘complete’ regression (see Equation 8.2), and *S_{e|_i}²* = the estimated variance of the residuals *e₁,...e_{i-1},e_{i+1},...,e_p* of the ‘reduced’ regression, i.e. linearly regressing *y* on *z₁,...z_{i-1},z_{i+1},...,z_p*. *RPSS_i* expresses the fractional contribution of source *z_i* to the total uncertainty in the model outcome *y*.

8.2.3 Metamodelling

The mathematical function (Equation 8.1) can also be approximated by a Taylor series by a second order polynomial, the so-called meta-model (Kleijnen, 1987):

$$\tilde{y} = \gamma_0 + \sum_{i=1}^p \gamma_i z_i + \sum_{i=1}^{p-1} \sum_{j=i+1}^p \gamma_{ij} z_i z_j \tag{8.6}$$

where *γ₀* is the overall mean, *γ_i* is the first-order effect of factor *z_p*, and *γ_{ij}* is the interaction between the factors *z_i* and *z_j*. *γ_i* can be considered as an absolute sensitivity measure, and reflects the absolute importance of factor *z_p*, measuring the absolute change Δ*y* of *y*, if *z_i* changes by an amount Δ*z_i*, while the other sources remain constant at their central values, and assuming no interactions (linear metamodel), or assuming that the sources *z_i* are uncorrelated. The model is linear in the regression parameters *γ*, and the number of parameters is equal to *l* = 1 + *p* + *p*(*p*-1)/2. At this stage, higher order effects (interactions and quadratic terms) can be considered, which is not the case for the linear regression model used by UNCSAM.

The coefficients *γ_i* or *γ_{ij}* can be estimated by linear regression, using ordinary least squares. Therefore, a number *N* (*N*>1) of factor settings (*z_{1k},...z_{pk}*) (*k*=1,...*N*) are chosen, and *N* simulation runs are performed with the model. Let *y^T* (= *y₁,...y_N*)^T denote the vector of the simulated model outcome, and let *Z* be

the matrix:

$$Z = \begin{pmatrix} 1 & z_{11}...z_{p1} & (z_{11}z_{21})...(z_{p-1,1}z_{p,1}) \\ \vdots & \vdots & \vdots \\ 1 & z_{1k}...z_{pk} & (z_{1k}z_{2k})...(z_{p-1,k}z_{p,k}) \\ \vdots & \vdots & \vdots \\ 1 & z_{1N}...z_{pN} & (z_{1N}z_{2N})...(z_{p-1,N}z_{p,N}) \end{pmatrix} \tag{8.7}$$

where *z_{jk}* = the value of factor *z_j* at the run *k* (*j*=1,...*p*; *k*=1,...*N*).

Then, it is known that:

$$\hat{\gamma} = (Z^T Z)^{-1} Z^T y^T \tag{8.8}$$

is the ordinary least square (OLS) estimator of the vector *γ^T* = (*γ₁,...γ_p,γ₁₂,...,γ_{1p},...,γ_{p-1,p}*)^T, only if *Z* is non-singular so that the inverse (*Z^TZ*) exists.

The mathematical analysis can be refined by adding a statistical submodel for the fitting errors *e_i* (*i*=1,...*l*). Kleijnen (1987) assumes that these errors are normally and independently distributed with a common variance of σ². Then the least squares algorithm yields the Best Linear Unbiased Estimators (BLUE). The variances of these estimators are located on the main diagonal of the variance-covariance matrix of *γ̂*:

$$cov(\hat{\gamma}) = (Z^T Z)^{-1} \sigma^2 \tag{8.9}$$

can be estimated using the mean squared residuals:

$$\sum_{k=1}^N (y_k - \tilde{y})^2 / (N-l) \quad (= \hat{\sigma}^2) \tag{8.10}$$

To test whether a coefficient of *γ_i* or *γ_{ij}* differs significantly from zero, the *t* statistic with *N*-1 degrees of freedom can be used:

$$t_{N-l,j} = (\hat{\gamma}_j - \gamma_j) / \hat{\sigma}_j \quad j=1,...,l \tag{8.10}$$

where *σ̂* = √*vâr*(*γ̂_j*), *γ_j* is the *j*-th element of vector *γ* (*j*=1,...*l*).

To perform the experiments in an effective and efficient way, and to reduce the number (*N*) of simulation runs, the technique of experimental design is applied in meta-modelling (for more details see Kleijnen (1987)).

However, metamodeling has here been used in a manner somewhat different from that employed originally, since instead of varying the model parameters in a systematic way using experimental designs, the values of the selected parameters are determined by means of Monte Carlo sampling using UNCSAM.

8.2.4 Metamodeling in combination with Monte Carlo sampling

In the analysis of the carbon cycle model (section 8.3), the technique of metamodeling was used for calculating the contribution of interacting parameters to the overall uncertainty. In contrast to the approach in section 8.2.3, the factors are not varied in a systematic way by means of experimental designs, but rather by using Monte Carlo sampling (as generated by UNCSAM). The constructed metamodel thus depends on the assumptions about the probability distribution of the model parameters, and this dependency is therefore checked by performing a robustness study.

In the case of the analysis presented in section 8.3, the original regression metamodel is transformed into a metamodel in which the data are centred around their averaged or central values, and normalized according to their standard deviation:

$$\tilde{y} = \beta_0 + \sum_{i=1}^p \beta_i x_i + \sum_{i=1}^{p-1} \sum_{j=i+1}^p \beta_{ij} x_i x_j \quad (8.12)$$

where $x_i = (z_i - c_i) / \sigma_i$ ($i=1, \dots, p$), with c_i = the central estimate of z_i and σ_i = the theoretical standard deviation of z_i (Harbers, 1993), and where β_0 is the overall mean, $\beta_i = \gamma_i \sigma_i$ is the first-order effect of factor x_i , and $\beta_{ij} = \gamma_{ij} \sigma_i \sigma_j$ is the contribution of the interaction between the factors x_i and x_j .

8.3 Analysis of the carbon cycle model

8.3.1 Introduction

This section presents a sensitivity and an uncertainty analysis of the carbon cycle model in IMAGE (experimental version 1.6).

The carbon cycle model employs an ocean box-diffusion model, a terrestrial biosphere model and an atmospheric box model, and simulates the atmospheric CO₂ concentration (output variable in this analysis). The model is extensively described in Chapter 6. The total number of model parameters is some several hundreds. Using an efficient screening technique, i.e. sequential bifurcation screening, Bettonvil (1991) identified around twenty of the important parameters in this large set. In the metamodeling studies of the separate ocean model and the terrestrial biota model (van Ham *et al.*, 1990; Kleijnen *et al.*, 1992) found similar important model parameters to those identified by Bettonvil (1991). These findings created a set of first choice parameters, consisting of 23 model parameters. However, since all these studies were based on the carbon cycle model of IMAGE (version 1.0), this list was extended with the addition of two feedback parameters for the temperature-related biogeochemical feedbacks, which have been incorporated in the carbon cycle model since the first version (den Elzen and Rotmans, 1993a). The final list now consists of the following model parameters:

- z_1 : the thickness of the warmer ocean mixed layer(m);
- z_2 : the thickness of the colder ocean mixed layer (m);
- z_3 : the total depth of the nine deeper layers (m);
- z_4 : residence time of CO₂ in the thin (warmer) ocean surface layer;
- z_5 : diffusion coefficient (m²/year)
- z_6 : fertilization factor (β);
- z_7 : residence time of humus in grassland (year);
- z_8 : residence time of humus in agricultural land(year);
- z_9 : fraction of charcoal by burning of branches;
- z_{10} : fraction of charcoal by burning of stems;
- z_{11} : humification fraction of closed tropical forest;
- z_{12} : humification fraction of open tropical forest;
- z_{13} : humification fraction of grassland;
- z_{14} : humification fraction of agricultural land;
- z_{15} : humification fraction of semi-desert area;
- z_{16} : life span of leaves in temperate forest (year);
- z_{17} : life span of stems in temperate forests (year);
- z_{18} : factor by which litter and soil respiration increases for a 10°C temperature increase;
- z_{19} : factor by which net primary production increases for a 10°C temperature increase.
- z_{20} : shift from temperate forest to agricultural land (Mha/year);
- z_{21} : shift from temperate forest to grassland (Mha/year);
- z_{22} : shift from temperate forest to open tropical forest (Mha/year);

- z_{23} : shift from human area to temperate forest (Mha/year);
 z_{24} : shift from agricultural land to temperate forest (Mha/year);
 z_{25} : shift from grassland to temperate forest (Mha/year);
 z_{26} : shift from open tropical forest to moderate forest (Mha/year);

8.3.2 Evaluation of uncertainty contribution

Scientific knowledge is used to determine the upper and lower limits of the parameters, as described *Table 8.1*. When selecting the parameter distribution, it is important to take into account the probabilistic properties of specific processes in the model, the empirical distribution of available data, and any information pertaining to the manner in which the system is expected to behave. If such this information is unavailable, the triangular distribution is to be recommended, for reasons given by Tiwari and Hobbie (1976): it is the least biased assumption under these circumstances; and moreover, in numerous cases, the results generated by the triangular distribution have proved to resemble results based on more complex distributions. In the subsequent analysis, the triangular distribution is adopted for all model parameters (*Table 8.1*). In order to evaluate the influence of this choice of the metamodel which is eventually constructed, a robustness study is performed, which involves a contrast with the uniform distribution (see last paragraph of this section).

A number of samples (selecting random variables from the triangular probability distribution) was generated using Latin Hypercube Sampling (UNCSAM). The size of this set of samples (in this case 190 samples were taken) should be sufficient to allow the distribution of the samples to approximate to the theoretical distribution (triangular distribution). For each sampled parameter set, the output variable, i.e. the atmospheric CO_2 -concentration in the year 2100, is simulated. The averaged model outcome is about 750 ppmv, with a 95%-confidence interval of [743;757], or $\bar{y} \pm 1\%$, which indicates that the number of samples is adequate for an accu-

Table 8.1: Factors with their central estimate, upper and lower bounds, and theoretical standard deviations for the triangular and the uniform distribution.

model parameter	minimum value	central value	maximum value	standard deviation (triangular distribution)	standard deviation (uniform distribution)
z_1	70.0	75.0	85.0	3.1	4.3
z_2	300.0	400.0	500.0	40.8	57.7
z_3	3000.0	3400.0	4000.0	205.5	288.7
z_4	15.0	20.0	25.0	2.0	2.9
z_5	1000.0	2000.0	4000.0	623.6	866.0
z_6	0.0	0.4	0.5	0.1	0.15
z_7	20.0	40.0	60.0	8.2	11.6
z_8	15.0	25.0	35.0	4.1	5.8
z_9	0.05	0.10	0.15	0.02	0.03
z_{10}	0.1	0.2	0.3	0.04	0.06
z_{11}	0.2	0.4	0.6	0.08	0.12
z_{12}	0.2	0.4	0.6	0.08	0.12
z_{13}	0.3	0.6	0.9	0.12	0.17
z_{14}	0.1	0.2	0.3	0.04	0.06
z_{15}	0.3	0.6	0.9	0.12	0.17
z_{16}	1.0	2.0	3.0	0.4	0.6
z_{17}	30.0	60.0	90.0	12.3	17.3
z_{18}	1.0	2.0	3.1	0.4	0.6
z_{19}	1.0	1.4	2.0	0.2	0.3
z_{20}	0.0	0.0	3.0	0.7	0.9
z_{21}	0.0	1.0	4.0	0.9	1.2
z_{22}	0.0	0.0	1.0	0.2	0.3
z_{23}	0.0	0.0	2.0	0.5	0.6
z_{24}	0.0	0.0	3.0	0.7	0.9
z_{25}	0.0	0.0	3.0	0.7	0.9
z_{26}	0.0	0.0	2.0	0.5	0.6

rate estimation of μ_y . In the case of a 2.5% deviation a set size as small as 40 would have been sufficient. The calculations of the confidence intervals assume that the model outcome y is normally distributed. This condition is fulfilled, since the Shapiro-Wilk (1965) measure is equal to 0.99, with an associated exceedence frequency of 0.84.

First metamodel: first order approach

In the first metamodel, the metamodel as described in section 8.2.4 (Equation 8.12) was used so that interactions between the model parameters were ignored. *Table 8.2* sets out the estimated effect parameters $\hat{\beta}_i$ ($i=1, \dots, 26$ ($=q$)), estimated by choosing

Table 8.2: Factors with estimated effects and *t*-values (*: significant at $\alpha = 0.05$).

factor	estimated effect: $\hat{\beta}_i$	t-statistics t_{163}
z_0	731.92	531.66*
z_1	-0.09	-0.27
z_2	-0.47	-1.36
z_3	-0.54	-1.58
z_4	9.00	26.63*
z_5	-1.64	-4.80*
z_6	-27.06	-76.81*
z_7	-12.28	-36.00*
z_8	-1.88	-5.41*
z_9	-2.82	-8.29*
z_{10}	-5.08	-14.99*
z_{11}	-2.60	-7.51*
z_{12}	-3.38	-9.73*
z_{13}	-15.18	-44.48*
z_{14}	-1.53	-4.40*
z_{15}	-4.51	-12.95*
z_{16}	-0.30	-0.84
z_{17}	-4.67	-13.65*
z_{18}	14.25	40.71*
z_{19}	-17.83	-52.96*
z_{20}	10.85	30.91*
z_{21}	6.87	20.03*
z_{22}	0.89	2.55*
z_{23}	-4.98	-14.67*
z_{24}	-8.51	-24.83*
z_{25}	-4.14	-12.10*
z_{26}	-0.62	-1.80

ordinary least squares. Table 8.2 presents the values of the Student statistic t_v with $v = N - q - 1 = 190 - 27 = 163$ degrees of freedom. The significant model parameters with $|t_{163}| > 1.960$ (the 97.5-quantile for the Student-distribution with 163 degrees of freedom), are indicated in the Table by an asterisk (*). The ten most important model parameters, next to z_0 , are in sequence of importance: z_6 , z_{19} , z_{13} , z_{18} , z_7 , z_{20} , z_4 , z_{24} , z_{21} , and z_{10} .

Validation of the first metamodel

The signs of estimated effects agree with what was expected on the basis of expert judgement, thus this first metamodel explains reasonably well. It now needs to be validated. Firstly, it is checked is run on whether the regression residuals $e_k = y_k - \hat{y}_k$ ($k=1, \dots, N$ ($=190$)) are independent of Z , and, moreover, on whether e_k are mutually independent, and distributed according to:

$\sim N(0, \sigma^2)$. The results of these checks were satisfactory (Harbers, 1993).

Further validation was performed in four separate steps, as described in detail in Harbers (1993), and briefly in the following:

(i) The simulated outcome y_k ($k=1, \dots, N$) is compared with the outcome of the meta-model $\hat{y}_k$, by calculating for all N simulation runs the relative residual (in %): $r_k = 100 (y_k - \hat{y}_k) / y_k$, ($k=1, \dots, N$). All r_k ($k=1, \dots, N$) are less than 1.7%, which is acceptable.

(ii) Cross-validation is performed, a technique whereby a number of times one run is left out of the whole estimation procedure for a metamodel (Kleijnen, 1987). One combination $((z_{11}, \dots, z_{p1})^T, y_1)$ ($p=26$) was deleted from the old data set (Z, y) , with the new data set, denoted as (Z_{-i}, y_{-i}) , and the whole estimation procedure was repeated. The outcome y_i was then compared with the outcome $\hat{y}_i$ of the new metamodel, by calculating the relative forecast errors i.e.: $e_{-i, k} = (\hat{y}_{-i, k} - y_k) / y_k$ ($k=1, \dots, N$), which were all less than 2%. This is satisfactory.

Next, the hypothesis is tested to discover whether the metamodel is valid or not, by using the *t*-test. The test variable $RSTUDENT_i$ is defined as (Bowerman and O'Connell, 1990):

$$RSTUDENT_i = \frac{y_i - \hat{y}_i}{\hat{S}_{y, \hat{y}_i}} \quad (8.13)$$

Since this test is based on the assumption that the residual errors are normally and independently distributed, this should first be checked by means of the calculation of the Shapiro-Wilk measure (Shapiro and Wilk, 1965). The calculated value of this measure was equal to 0.98, with an associated exceedence frequency of 0.22 ($\alpha=0.05$). Therefore, the hypothesis that the residual errors are normally distributed is not rejected.

We now assume that the normally and independently distributed output variable y_i has a common variance (σ^2),

$$\text{equal to} \quad \sum_{k=1}^N (y_k - \bar{y})^2 / (N-1)$$

The variance of $\hat{y}_i$ is equal to: $\hat{S}_{y, \hat{y}_i}^2 = z_i c \hat{\sigma}^2 (\hat{\beta}_i) z_i^T$, with the vectors z_i and $\hat{\beta}_i$. The

variance-covariance matrix of $\hat{\beta}_i$ is estimated: $\text{cov}(\hat{\beta}_i) = (Z_i^T Z_i)^{-1} \hat{\sigma}^2$.

Now, the test variable $RSTUDENT_i$ has the Student distribution, with $u = (N-1) - q - 1 = 189 - 27 = 162$ degrees of freedom. This probability distribution can be approximated by the standard-normal distribution (Kleijnen, 1987). The significance level is equal to 0.05, and now based on the inequality of Bonferroni, the hypothesis (the metamodel is valid) is rejected, if: $\exists i: i \in \{1, \dots, N\}$ for which $|RSTUDENT_i| > t_{162}$. Here, all $|RSTUDENT_i|$ values are lower, and therefore the hypothesis is not rejected.

(iii) Eight extra runs are performed using new combinations of the model parameters, sampled from their triangular distribution. The metamodel based on 190 runs can now calculate the value $\hat{y}_{N+1}$, which is compared to the $(N+1)$ th outcome of the simulation model. The extra runs and the results of these experiments are presented in Table 8.3. For all extra runs the relative residuals (in %) are less than 1.6 %, which is acceptable.

(iv) Finally the regression analysis was performed without the non-significant model parameters z_1, z_2, z_3, z_{16} , and z_{26} . The final results in terms of significant regression parameters remain about the same, and thus this metamodel is accepted as being valid.

Robustness study

In this paragraph the robustness of the linearity of the metamodel, as well as the final significant parameters found, to the choice of the probability distribution for the model parameters is studied. This robustness study assumes all selected model parameters to be uniformly distributed (Table 8.1).

A set of samples (here 130 ($=M$) samples) from the uniform distribution is generated by means of Latin Hypercube sampling, and the model outcome is simulated. The averaged model outcome $\bar{y}$ is equal to 757, with a 95%-confidence interval of $\bar{y} \pm 1.5\%$, which indicates that the size of the set of samples is accepted as adequate for accurately estimating μ_y .

The linear metamodel of the previous paragraph is now used, and the regression parameters $\hat{\beta}_i$ ($i=1, \dots, 26$ ($=q$)) are again esti-

Table 8.3: The estimated and the simulated CO_2 concentration and the resulting relative residuals.

extra run	simulation (y_{N+i})	metamodel ($\hat{y}$)	relative residuals $100 * \frac{y_{N+i} - \hat{y}}{y_{N+i}}$ (in %)
1	856.5	851.7	0.56
2	738.4	738.0	0.06
3	787.4	784.9	0.32
4	784.2	785.3	-0.14
5	819.2	815.3	0.48
6	721.7	733.8	-1.54
7	734.8	733.8	0.13
8	709.7	712.5	-0.36

mated using ordinary least squares (Table 8.4). This Table also sets out the values of the Student statistic t_i with $v = N - q - 1 = M - 27 = 103$ degrees of freedom. The significant model parameters, for which $|t_{103}| > 1.987$ (the 97.5-quantile for the Student-distribution with 103 degrees of freedom), are indicated by an asterisk (*). To compare these results with the results of the first metamodel (sampling from a triangular distribution), the latter are also presented in this Table.

This Table shows that almost the same parameters now appeared to be non-significant, except for the regression parameter β_{22} . Moreover, the sequence in importance is the same for the first ten most important model parameters, and the sequence of the remaining significant model parameters show minor changes in ranking.

Again the metamodel (sampling uniform distribution) needs to be validated:

(i) The relative residual errors of the M runs are all less than 2.5%, which is acceptable.

(ii) The results of cross-validation are satisfactory. All relative errors $(y_k - \hat{y}_{-ik}) / y_k \cdot 100$ ($k=1, \dots, M$) are less than 3%. The test variable $RSTUDENT_i$ is distributed according to the Student distribution with $(N - 1) - q = M - 1 - 27 = 103$ degrees of freedom, which is approximated by the standard normal distribution. Now, the hypothesis (the metamodel is valid) is again not rejected, which indi-

Table 8.4: Model parameters with their estimated effects and t -values for the uniform distribution and the triangular distribution, in sequence of their importance.

Uniform distribution			Triangular distribution		
model parameter	estimated effect $\hat{\beta}_i$	t_{103}	model parameter	estimated effect $\hat{\beta}_i$	t_{163}
z_0	732.89	220.74*	z_0	731.92	531.66*
z_6	-36.62	-50.41*	z_6	-27.06	-76.81*
z_{19}	-25.71	-35.53*	z_{19}	-17.83	-52.96*
z_{13}	-20.62	-28.29*	z_{13}	-15.18	-44.48*
z_{18}	20.10	27.91*	z_{18}	14.25	40.71*
z_7	-16.80	-23.28*	z_7	-12.28	-36.00*
z_{20}	13.21	18.32*	z_{20}	10.85	30.91*
z_4	12.86	17.81*	z_4	9.00	26.63*
z_{24}	-10.29	-14.20*	z_{24}	-8.51	-24.83*
z_{21}	9.49	13.10*	z_{21}	6.87	20.03*
z_{10}	-7.83	-10.87*	z_{10}	-5.08	-14.99*
z_{17}	-6.65	-9.23*	z_{23}	-4.98	-14.67*
z_{23}	-6.31	-8.74*	z_{17}	-4.67	-13.65*
z_{15}	-6.09	-8.37*	z_{15}	-4.51	-12.95*
z_{25}	-4.80	-6.63*	z_{25}	-4.14	-12.10*
z_9	-4.58	-6.33*	z_{12}	-3.38	-9.73*
z_{12}	-4.22	-5.82*	z_9	-2.82	-8.29*
z_8	-3.15	-4.36*	z_{11}	-2.60	-7.51*
z_{11}	-2.81	-3.89*	z_8	-1.88	-5.41*
z_{14}	-2.03	-2.81*	z_5	-1.64	-4.80*
z_5	-1.49	-2.06*	z_{14}	-1.53	-4.40*
z_2	-1.13	-1.57*	z_{22}	0.89	2.55*
z_{26}	-0.85	-1.18	z_{26}	-0.62	-1.80
z_{22}	0.74	1.01	z_3	-0.54	-1.58
z_{16}	-0.40	-0.55	z_2	-0.47	-1.36
z_3	-0.13	-0.18	z_{16}	-0.30	-0.84
z_1	0.07	0.09	z_1	-0.09	-0.27

cates a valid metamodel.

(iii) Eight extra runs were performed using new combinations of the model parameters. The metamodel can now calculate the value $\hat{y}_{N+1}$, which is compared to the $(N+1)$ th outcome of the simulation model. For all extra runs the relative residuals (in %) are less than 6%, which is acceptable.

(iv) Finally the regression analysis is repeated without the non-significant model parameters, which generated the same significant parameters. Thus, this metamodel is accepted.

In conclusion, the metamodel associated with sampling the model parameters from

the uniform distribution is of the same form as the metamodel associated with sampling the parameters from the triangular distribution. Thus, based on these two extreme distributions it can be concluded that interactions play a minor role in the total uncertainty. In the next paragraph the total uncertainty of the model outcome for these two extreme distributions will be examined.

Conclusions

Following on the validation procedure and the robustness study the first order metamodel can be accepted. It can therefore be concluded that the interactions between

Table 8.5: Statistical information on the atmospheric CO₂ concentration for the years 2000, 2050, and 2100 for the BaU90 and AP90 scenario.

Statistics	BaU90 scenario			AP90 scenario		
	2000	2050	2100	2000	2050	2100
mean	364.1	509.1	748.7	376.8	422.4	430.9
standard deviation	8.3	25.7	47.0	8.7	21.5	25.8
2.5%-percentile	348.7	456.8	643.7	360.7	376.8	372.3
97.5%-percentile	380.8	564.2	840.1	394.7	467.8	481.1

model parameters and quadratic terms do not play a significant role. The same result was found in the analysis of the carbon cycle model by Bettonvil (1991). However, in the previous metamodeling study on the separate ocean- and terrestrial biosphere model of the carbon cycle model (van Ham *et al.*, 1990; Kleijnen *et al.*, 1992), for the final metamodel of the ocean model second order effects, the three interactions (z_2z_3 , z_3z_4 and z_1z_3), and one quadratic term (z_3^2), were also identified as significant factors. For the final metamodel of the terrestrial biosphere model no significant second order factors were found. A possible explanation for this discrepancy would be that in the carbon cycle model the model outcome is more affected by the biosphere parameters than the ocean parameters (as is also suggested by the priority order of the model parameters).

The uncertainty contribution of the model parameters to the total uncertainty in the model outcome (atmospheric CO₂ concentration in 2100 for the IPCC-1990 Business-as-Usual (BaU90) scenario are represented by their regression parameters as presented in Table 8.4. The priority order of the factors describing the atmospheric CO₂ concentration is, in decreasing order of importance:

- z_6 : fertilization factor (β);
- z_{19} : factor by which net primary production increases for a 10°C temperature increase.
- z_{13} : humification fraction of grassland;
- z_{18} : factor by which the litter and soil respiration increases for a 10°C temperature increase;
- z_7 : residence time of humus in grassland (year);

- z_{20} : shift from temperate forest to agricultural land (Mha/year);
- z_4 : residence time of CO₂ in the thin (warmer) ocean surface layer;
- z_{24} : shift from agricultural land to temperate forest (Mha/year);
- z_{21} : shift from temperate forest to grassland (Mha/year);
- z_{10} : fraction of charcoal by burning of leaves, in grassland;

The fertilization factor (z_6), and the temperature feedback parameters (z_{19} and z_{18}) appear to be of major importance, a result which was expected. These factors directly influence the net primary production process, the main flow of carbon dioxide between the atmosphere and the terrestrial biosphere. As indicated above, it was expected that the ocean parameters would be of minor importance compared to the terrestrial biosphere parameters, but it is surprising that only one ocean parameter is among the ten most important parameters.

8.3.3 Evaluation of total uncertainty

Based on the sampled data (triangular distribution) and the associated simulated CO₂-concentration according to the IPCC-1990 Business-as-Usual (BaU90) scenario and the Accelerated Policies (AP90) scenarios, the total uncertainty is now calculated using the software package UNCSAM.

Table 8.5 gives the mean, standard deviation, and the 2.5% and 97.5% percentiles in the shorter term (2000), halfway (2050), and at the end of the simulation period (2100) according to the BaU90 and AP90 scenarios. The relative uncertainty, i.e. the deviation of

Figure 8.1: Uncertainty in the atmospheric CO₂ concentration for the IPCC-1990 Business-as-Usual and Accelerated Policies scenario (uncertainty range represents the '95% confidence band' range between the 2.5% and 97.5% percentiles).

the percentiles from the mean value, increases in time for both scenarios up to: about 13% for the BaU90 scenario and about 12% for the AP90 scenario by 2100. However, in the AP90 scenario the rate of increase slows down after 2050, which is mainly a result of the stabilization of the mean atmospheric CO₂-concentration.

Figure 8.1 presents the mean and uncertainty range (here the '95% confidence band' range between the 2.5% and 97.5% percentiles) for the atmospheric CO₂ concentration for the BaU90 scenario and the AP90 scenario. The absolute uncertainty (defined as the absolute change in model-outcome due to

variations in model parameters) increases in time, because most important model parameters (such as the fertilization factor) are directly dependent on the model outcome (CO₂-concentration), and therefore their effect due to changes and their values is more significant at higher CO₂ concentration levels, as simulated at the end of the 21st century, than at lower CO₂ values.

The simulated CO₂ concentration for the reference case (all model parameters set on their central estimates, as presented in Chapter 6) does not significantly differ from the mean values generated here, and is less than 1-2%. The overlap area of both uncer-

Figure 8.2a: Frequency histogram for the atmospheric CO₂ concentration for the IPCC-1990 Business-as-Usual scenario, assuming all chosen model parameters triangularly distributed for the year 2100 (uncertainty range represents the '95% confidence band' range between the 2.5% and 97.5% percentiles).

Figure 8.2b: Frequency histogram for the atmospheric CO₂ concentration for the IPCC-1990 Business-as-Usual scenario, assuming all chosen model parameters uniformly distributed for the year 2100 (uncertainty range represents the '95% confidence band' range between the 2.5% and 97.5% percentiles).

inside uncertainty range (BaU90 scenario),
uniform distribution

outside uncertainty range (BaU90 scenario),
uniform distribution

tainty ranges represents a period up to 2050 in which the low CO₂ concentration projection (2.5% percentile) of the BaU90 scenario is lower than the high CO₂ concentration projection (97.5% percentile) of the AP90 scenario.

As an indication of how these ranges between the 2.5% and 97.5% percentiles depend on the choice of the distribution for the parameters (here a triangular distribution), this Figure also presents, for the BaU90 scenario only, the uncertainty range based on the 2.5% and 97.5% percentiles assuming all model parameters are uniformly distributed (less centred distribution). Still the range of [610;866] for the percentiles by the year 2100 is rather small, especially compared to the extreme range based on setting all model parameters on their maximum and/or minimum value, which is equal to [480;1170] at the end of the simulation period, in the year 2100.

Figures 8.2a and 8.2b show the histogram of the relative frequency (uncertainty range is also indicated in this Figure) for the year 2100 for the BaU90 scenario assuming all chosen model parameters are triangularly and uniformly distributed, respectively. This Figure shows, as expected, that the assumption of uniformly distributed model parameters not only results in a larger uncertainty range, but also in less centred model outcomes.

8.4 Analysis of the halocarbon model

8.4.1 Introduction

This paragraph presents an uncertainty analysis of the halocarbon model. The model, which is briefly described in Chapter 3, and is extensively described in Chapter 10, contains about 75-100 parameters. This set has been reduced in the light of the modeller's knowledge about the model parameters, and in case of some parameters by using a simple sensitivity analysis (studying the effect on the model output when these model parameters are varied, while the other parameters remain constant), to a final list of 46 selected model parameters, (with their central value, and lower and upper bounds given in Table 8.6).

In the analysis of the halocarbon model, the chosen output variables are the following: the atmospheric CFC-11 concentration, the atmospheric CFC-12 concentration and the atmospheric chlorine concentration over the time period 1990 to 2100 for two policy scenarios, namely: the Montreal Protocol and the London Amendments. The CFC-11 concentration depends only on the model parameters $w_1, \dots, w_{10}$, and the CFC-12 concentration on $w_1, w_{11}, \dots, w_{21}$, while the atmospheric chlorine concentration depends on all of the model parameters.

Since no interactions between the model parameters are expected, UNCSAM is used

Table 8.6: Model parameters with their central estimate, upper and lower values

	min.	central	max.
w_1 : fraction of the total CFC production by the developing world.	0.1	0.2	0.3
w_2 : fraction of the CFC-11 production for closed cell foams released to the atmosphere.	0.1	0.25	0.5
w_3 : fraction of the CFC-11 production for aerosol applications released to the atmosphere	0.1	0.25	0.5
w_4 : fraction of the CFC-11 production for refrigerants released to the atmosphere.	0.05	0.1	0.25
w_5 : annual fraction that leaks from landfill sites or delayed-release box into the atmosphere.	0.05	0.07	0.10
w_6 : atmospheric lifetime of CFC-11 (years) (Prather <i>et al.</i> , 1992).	42	55	66
w_7 : fraction of CFC-11 production in the end use category aerosols.	0.0	0.3	0.5
w_8 : fraction of CFC-11 production in the end use category closed cell foams.	0.0	0.6	0.8
w_9 : fraction of CFC-11 production in the end use category refrigeration.	0.0	0.6	0.8
w_{10} : fraction of CFC-11 production lost by manufacture (fugitive emissions).	0.005	0.02	0.04
w_{11} : delay time between the production of CFC-12 for the end use category refrigerants and the end of the consumption (years).	2	4	10
w_{12} : fraction of CFC-12 production for closed cell foams released to atmosphere	0.1	0.25	0.5
w_{13} : fraction of CFC-12 production for aerosol application released to atmosphere	0.1	0.666	0.8
w_{14} : fraction of CFC-12 production for hermetically sealed refrigerants released to the atmosphere.	0.05	0.083	0.15
w_{15} : fraction of CFC-12 production for non-hermetically sealed refrigerants released to the atmosphere.	0.05	0.12	0.2
w_{16} : annual fraction that leaks from landfill sites or delayed-release box into the atmosphere (CFC-12).	0.10	0.25	0.30
w_{17} : atmospheric lifetime of CFC-12 (years) (Prather <i>et al.</i> , 1992).	95	116	130
w_{18} : fraction of CFC-12 production in the end use category aerosols.	0.0	0.09	0.5
w_{19} : fraction of CFC-12 production in the end use category closed cell foams.	0.0	0.19	0.8
w_{20} : fraction of CFC-12 production in the end use refrigeration.	0.0	0.19	0.8
w_{21} : fraction of CFC-12 production lost by manufacture (fugitive emissions).	0.005	0.055	0.06
w_{22} : atmospheric lifetime of CFC-113 (years) (Prather <i>et al.</i> , 1992).	75	110	144
w_{23} : atmospheric lifetime of CFC-114 (years) (Prather <i>et al.</i> , 1992).	197	220	264
w_{24} : fraction of the CFC-114 production for hermetically sealed refrigerants released to the atmosphere.	0.10	0.25	0.5
w_{25} : annual fraction that leaks from landfill sites or delayed-release box into the atmosphere (CFC-114).	0.05	0.30	0.40
w_{26} : atmospheric lifetime of CFC-115 (years) (Prather <i>et al.</i> , 1992).	400	550	800
w_{27} : fraction of the CFC-114 production for hermetically sealed refrigerants released to the atmosphere.	0.05	0.15	0.25
w_{28} : annual fraction that leaks from landfill sites or delayed-release box into the atmosphere (CFC-115).	0.10	0.20	0.3
w_{29} : atmospheric lifetime of CCl_4 (years) (Prather <i>et al.</i> , 1992).	30	47	58
w_{30} : atmospheric lifetime of CH_2Cl_2 (years) (Prather <i>et al.</i> , 1992).	5.1	6.1	6.4
w_{31} : stratospheric lifetime of CH_2Cl_2 (Prather <i>et al.</i> , 1992).	40	47	53
w_{32} : reaction rate coefficient of CH_2Cl_2 with OH radicals	2.4	2.7	3.0
w_{33} : stratospheric lifetime of HCFC-22 (Prather <i>et al.</i> , 1992).	220	240	260
w_{34} : reaction rate coefficient of HCFC-22 with OH radicals	1.0	1.1	1.2
w_{35} : fraction of the HCFC-22 production for hermetically sealed refrigerants released to the atmosphere.	0.05	0.1	0.15
w_{36} : fraction of HCFC-22 production for closed foams released to the atmosphere	0.10	0.25	0.5
w_{37} : fraction of HCFC-22 production for non-hermetically sealed refrigerants released to the atmosphere.	0.05	0.1	0.2
w_{38} : annual fraction that leaks from the land fill sites or delayed-release box into the atmosphere (HCFC-22)	0.04	0.08	0.12
w_{39} : fraction of HCFC-22 production in the end use category aerosols.	0.0	0.09	0.5
w_{40} : fraction of HCFC-22 production in the end use category closed cell foams.	0.0	0.5	0.6
w_{41} : fraction of HCFC-22 production in the end use category h. refrigerants	0.0	0.2	0.6
w_{42} : stratospheric lifetime of HCFC-X (Prather <i>et al.</i> , 1992).	110	125	140
w_{43} : reaction rate coefficient of HCFC-X with OH radicals	1.0	1.1	1.2
w_{44} : stratospheric lifetime of HCFC-Y (Prather <i>et al.</i> , 1992).	65	75	85
w_{45} : reaction rate coefficient of HCFC-Y with OH radicals	3.0	3.5	4.0
w_{46} : reaction rate coefficient of HCFC-Z with OH radicals	0.55	0.63	0.7

Table 8.7: Statistical information on the atmospheric CFC-11, CFC-12 and chlorine concentration associated with the London Amendments and the Montreal Protocol.

Statistics	London Amendments			Montreal Protocol		
	2000	2050	2100	2000	2050	2100
CFC-11:						
mean	303.0	163.3	66.0	313.7	450.8	502.5
standard deviation	7.9	14.9	11.3	8.9	25.4	36.5
2.5% percentile	287.2	131.2	43.0	295.0	398.6	429.5
97.5% percentile	319.4	189.0	87.0	331.5	495.3	564.5
CFC-12:						
mean	564.4	411.0	264.0	574.8	842.5	1000.0
standard deviation	9.0	17.3	17.6	11.8	22.5	35.3
2.5% percentile	548.9	377.2	228.5	554.3	796.4	932.0
97.5% percentile	582.7	446.7	297.3	597.8	882.9	1063.
chlorine:						
mean	4.0	2.55	1.6	4.2	7.3	9.1
standard deviation	0.05	0.07	0.05	0.05	0.1	0.2
2.5% percentile	3.9	2.4	1.45	4.1	7.0	8.7
97.5% percentile	4.0	2.7	1.7	4.3	7.5	9.4

for the complete uncertainty analysis, including the calculation of the individual contribution of the various sources to the overall uncertainty.

8.4.2 Evaluation of total uncertainty

For the uncertainty analysis, the probability distributions for all model parameters are specified as triangular distributions, with the calculated standard deviation. In the analysis, 300 samples were taken by means of Latin Hypercube sampling.

Some of the model parameters represent the fractions of the halocarbon production for a specific end-use category, and the values are therefore restricted by constraints. These are: $w_7 + w_8 + w_9 = 1$; $w_{18} + w_{19} + w_{20} = 1$; $w_{39} + w_{40} + w_{41} = 1$. Therefore the parameters w_9 , w_{20} , and w_{41} are left out in the sampling, since these are specified in the model by these conditions. In fact, three samples are not accepted for the analysis, since in these samples one of the three conditions is not fulfilled (the sum of fractions is higher than one). A test is now performed to discover whether 297 samples are sufficiently repre-

sentative to approximate the theoretical distribution. This test involves calculating the relative errors between the key statistics (averaged value, standard deviation, and percentiles) of the sampled information and the key statistics of the theoretical distribution (triangular distribution). These errors were less than 0.1%, and thus the size of the sampling set is deemed to be representative. In addition, a check is run on whether the cumulative distribution function according to sampling from the Latin Hypercube sampling approximates the theoretical distribution for all sampled model parameters satisfactorily.

Taking the 297 samples, the associated model simulations were performed, with as output variables the atmospheric CFC-11 -, CFC-12 -, and chlorine concentration.

The uncertainty is presented in Table 8.7 with the mean, standard deviation, and the 2.5% and 97.5% percentile in the shorter term (2000), halfway (2050), and at the end of the simulation period (2100).

Figures 8.3, 8.4 and 8.5 plot the trajectories of the mean and uncertainty ranges (based on

Figure 8.3: Uncertainty in the atmospheric CFC-11 concentration for the London Amendments and the Montreal Protocol (uncertainty range represents the '95% confidence band' range between the 2.5% and 97.5% percentiles).

— mean value
 [lighter shaded] uncertainty range (London Amendments)
 [darker shaded] uncertainty range (Montreal Protocol)
 [darkest shaded] overlap area of both uncertainty ranges (London Amendments and Montreal Protocol)

the 2.5% and 97.5% percentiles) during the simulation period 1990 to 2100 for the two policy scenarios regarding atmospheric CFC-11 -, CFC-12 -, and chlorine concentration.

For all model outcomes, the reference value correspond well with the mean-value (less than 1%). For all three model outcomes the absolute uncertainty range increases for the Montreal Protocol (hereafter referred to as MP), and decreases for the London Amendments (hereafter LA), as a direct result of the increase or decrease in the concentrations.

The relative uncertainty, expressed by the

deviation of the percentiles from the mean, slightly increases in future for all three output variables for both policies (up to about 10-15% (MP) and 30-35% (LA) for the CFC-11 concentration, about 5% (MP) and 10-12% (LA) for the CFC-12 concentration, and about 3-5% (MP) and 8-10% (LA) for the chlorine concentration). The relative uncertainties in the final atmospheric chlorine atoms per molecule of all halocarbons in the atmosphere) are somewhat less significant compared to the uncertainties in the concentration of CFC-11 and CFC-12 (presently

Figure 8.4: Uncertainty in the atmospheric CFC-12 concentration for the London Amendments and the Montreal Protocol (uncertainty range represents the '95% confidence band' range between the 2.5% and 97.5% percentiles).

— mean value
 [lighter shaded] uncertainty range (London Amendments)
 [darker shaded] uncertainty range (Montreal Protocol)
 [darkest shaded] overlap area of both uncertainty ranges (London Amendments and Montreal Protocol)

Figure 8.5: Uncertainty in the atmospheric chlorine concentration for the London Amendments and the Montreal Protocol (uncertainty range represents the '95% confidence band' ranges between the 2.5% and 97.5% percentiles).

contributing 50% to the chlorine concentration). This can be explained by the fact that the uncertainties involving the other halocarbons are of a lesser order, which was to be expected given their short atmospheric lifetimes.

8.4.3 Evaluation of uncertainty contributions

Before calculating the uncertainty contributions, the validity of the simple linear regression model will first be tested in approximating the simulated model responses. The

results for the R^2 (COD) for the years 2000, 2050 and 2100 show that this is the case ($R^2 \sim 1$, for CFC-11 and chlorine, and >0.95 for CFC-12). The results of the uncertainty contributions (in *SRC* and *RPSS*) of the most important model parameters for the three output variables for the London Amendments are presented in Table 8.7, and graphically (*RPSS*) depicted in Figure 8.6, 8.7, and 8.8.

The ranking of the important (in terms of their influence on total uncertainty) model parameters is equal for both uncertainty

Figure 8.6: Contribution of the various model parameters to the uncertainty in the atmospheric CFC-11 concentration for the London Amendments. The uncertainty contribution is measured by Relative Partial Sum-of-Squares (RPSS).

Table 8.8: Uncertainty contributions and ranking of the uncertainty sources for the atmospheric CFC-11, CFC-12 and chlorine concentration under the London Amendments.

London Amendments	2000			2050			2100		
	RPSS	SRC	ranking	RPSS	SRC	ranking	RPSS	SRC	ranking
CFC-11:									
w_5	0.47	0.69	(1)	0.01	-0.09	(3)	0.01	-0.10	(2)
w_6	0.33	0.57	(2)	0.96	0.98	(1)	0.98	0.99	(1)
w_7	0.15	0.39	(3)	0.00	-0.04	(4)	0.00	-0.03	(4)
w_2	0.01	0.12	(4)	0.00	-0.01	(7)	0.00	-0.01	(6)
w_l	0.00	0.10	(5)	0.03	0.16	(2)	0.01	0.09	(3)
w_{11}	0.00	0.07	(7)	0.00	0.02	(5)	0.00	0.01	(5)
CFC-12:									
w_{12}	0.44	0.66	(1)	0.00	0.02	(4)	0.00	0.02	(4)
w_{13}	0.31	0.56	(2)	0.00	0.00	(12)	0.00	0.00	(19)
w_{17}	0.10	0.32	(3)	0.61	0.78	(1)	0.61	0.92	(1)
w_{16}	0.09	0.31	(4)	0.00	-0.02	(5)	0.00	-0.01	(5)
w_{15}	0.01	0.10	(5)	0.00	-0.00	(43)	0.00	0.00	(42)
w_{11}	0.00	0.08	(7)	0.35	0.59	(2)	0.35	0.37	(2)
w_l	0.00	0.06	(8)	0.04	0.20	(3)	0.04	0.13	(3)
chlorine:									
w_5	0.17	0.42	(1)	0.00	-0.06	(8)	0.00	-0.06	(7)
w_l	0.14	0.37	(2)	0.10	0.31	(4)	0.04	0.19	(6)
w_{32}	0.13	-0.36	(3)	0.00	-0.00	(24)	0.00	-0.00	(17)
w_6	0.12	0.35	(4)	0.44	0.66	(1)	0.38	0.62	(1)
w_{12}	0.11	0.33	(5)	0.00	0.02	(13)	0.00	0.01	(13)
w_{29}	0.09	0.30	(6)	0.12	0.35	(3)	0.06	0.25	(4)
w_{17}	0.02	0.15	(9)	0.16	0.41	(2)	0.36	0.60	(2)
w_{22}	0.00	0.06	(16)	0.04	0.21	(6)	0.09	0.30	(3)
w_{11}	0.00	0.04	(19)	0.09	0.31	(5)	0.06	0.24	(5)

quantities by virtue of their definitions.

In the case of CFC-11, the four model parameters as depicted in Figure 8.6, explain more than 95% of the total uncertainty (according to the sum of $100 \cdot RPSS_i$). The contribution of w_6 (atmospheric lifetime CFC-11) increases in time, with a maximum value around 2045 (to be expected since the lifetime has a central value of 55 years). The contribution to the total uncertainty for the other mentioned parameters decreases as time goes by, since all these parameters are related to the future production of CFC-11, which is to be phased out by 2000. Even over the period 1990-2100, w_6 is virtually the most important parameter, excepting the model parameter w_5 expressing the leakage fraction of the emissions from the landfill

sites (halocarbon-bank) which is of more importance. The increase in importance of the model parameter w_l after 2000 is due to delayed phase-out in the developing world (London Amendments).

In the case of CFC-12, an analogous trajectory of the uncertainty contributions of the various model parameters is found as for CFC-11. The importance of the model parameter w_{17} , the atmospheric lifetime of CFC-12 increases in time, with a maximum contribution to the total uncertainty after 2100 (central value of w_{17} equal to 116 years). An important difference with the previous conclusions is the significant influence of the model parameter (w_{11}), the averaged lifetime of a refrigerator, although its influence decreases when the influence of the

Figure 8.7: Contribution of the various model parameters to the uncertainty in the atmospheric CFC-12 concentration for the London Amendments. The uncertainty contribution is measured by Relative Partial Sum-of-Squares (RPSS).

parameter w_{17} increases.

For chlorine, again the five most important model parameters, depicted in Figure 8.8, explain more than 90% (RPSS) of the total uncertainty on the longer term. In the short term, their individual contribution of the six most important model parameters is almost equal, and these parameters are mostly non-atmospheric lifetime parameters. However, for the long term, the contribution to the total uncertainty is mainly dominated by the two model parameters, the atmospheric lifetime of CFC-11 and CFC-12. Both gases are presently also the main contribu-

tors to atmospheric chlorine loading (see Chapter 10).

8.5 Analysis of IMAGE

8.5.1 Introduction

The model IMAGE (experimental version 1.6), as described in Chapter 3, consists of several modules, each of which consists of a number of model parameters while lies between a hundred and several thousands. In the final analysis described in this paragraph,

Figure 8.8: Contribution of the various model parameters to the uncertainty in the atmospheric chlorine concentration for the London Amendments. The uncertainty contribution is measured by Relative Partial Sum-of-Squares (RPSS).

Table 8.9: Model parameters with their central estimate, upper and lower values.

	min.	central	max.
v_1 : atmospheric lifetime of N_2O (years) (IPCC, 1992).	110	150	170
v_2 : reaction rate between OH and CH_4	1.45	1.71	2.1
v_3 : reaction rate between OH and CO	7.1	7.53	8.0
v_4 : reaction rate between CO and tropospheric ozone	0.1	0.15	0.2
v_5 : rate describing the influence of tropospheric ozone on the production of OH	0.45	0.5	0.55
v_6 : rate describing the influence of NO_x on the production of OH	0.20	0.3	0.40
v_7 : rate by which tropospheric CH_4 is removed from the troposphere by combination of transport to the stratosphere and oxidation of OH	0.007	0.0094	0.011

we are interested in the total uncertainty in the modelled output of radiative forcing (due to changes in the concentrations of greenhouse gases), and surface temperature increase for the two IPCC-1990 scenarios, as a result of the cumulative uncertainties in the whole chain, from the emissions of the greenhouse gases, changes in concentrations, changes in radiative forcing, to the temperature increase.

A considerable reduction of these sources is now needed for a comprehensive analysis of the IMAGE model (experimental version 1.6) as a whole. This has been performed by regarding only the important model parameters (in the long term) for the halocarbon model and the carbon cycle model, as was found in the previous paragraphs: $z_6, z_{19}, z_{13}, z_{18}, z_7, z_{20}, z_4, z_{24}, z_{21}$, and z_{10} of the carbon cycle model, and $w_1, w_5, w_6, w_{11}, w_{17}, w_{22}$, and w_{29} of the halocarbon model.

For the atmospheric chemistry model, Krol and van den Woerd (1994) have already indicated the main model parameters of this model, which are listed in Table 8.9.

The last set of parameters describing the conversion of radiative forcing into temperature increase are the parameters of the climate model. Expert knowledge yields the main model parameter of this model, the climate sensitivity (v_8), which is the global-mean surface temperature increase following doubling of CO_2 . This parameter has a central estimate value of $2.5^\circ C$, and a range between 1.5 and $4.5^\circ C$ (IPCC, 1992).

For the uncertainty analysis UNCSAM is

used. The next paragraph evaluates the total uncertainty. The separate contributions of the individual sources to the total uncertainty is not assessed here, because of the expected significant contribution of a number of interacting model parameters on the total uncertainty (like the interaction between the climate sensitivity and the temperature terrestrial feedbacks in the carbon cycle), which cannot be quantified by UNCSAM. Moreover, time was too short for applying the technique of metamodelling.

8.5.2 Evaluation of total uncertainty

The central estimate, and the upper and lower bounds of the selected model parameters have already been described in the previous paragraph. The probability distribution of the model parameters is again specified by the triangular distribution.

As already mentioned, the chosen output variables are: radiative forcing, and global mean surface temperature increase. Using UNCSAM, 300 samples were generated, and used for the simulation of the model outcomes.

Table 8.10 shows the mean, standard deviation, and the 2.5% and 97.5% percentile at the shorter term (2000), halfway (2050), and at the end of the simulation period for both model outcomes. This Table shows that in the case of radiative forcing (in Wm^{-2}), 95% of all final outcomes fall in the range $[8.2; 10.0]$ for the BaU90 scenario. The extreme range generated by setting all

Table 8.10: Statistical information on radiative forcing and surface temperature increase for the years 2000, 2050, and 2100 for the BaU90 and AP90 scenario.

Statistics	BaU90 scenario			AP90 scenario		
	2000	2050	2100	2000	2050	2100
radiative forcing:						
mean	2.5	6.0	9.1	2.4	3.5	3.55
standard deviation	0.15	0.35	0.45	0.15	0.35	0.4
2.5% percentile	2.25	5.30	8.20	2.15	2.85	2.9
97.5% percentile	2.80	6.70	10.0	2.7	4.1	4.4
surface temperature increase:						
mean	1.00	2.80	4.70	1.0	1.8	2.1
standard deviation	0.20	0.65	1.10	0.2	0.4	0.5
2.5% percentile	0.70	1.70	2.80	0.7	1.15	1.3
97.5% percentile	1.40	4.10	6.80	1.35	2.8	3.25

selected model parameters at the maximum value and/or minimum value is: [5.9;12.5]. The maximum outcome of the simulated outcome of UNCSAM is equal to 10.5 Wm^{-2} , and the minimum outcome equal to 8.8 Wm^{-2} . This difference with the original values can be explained by the chosen sampling technique (Latin Hypercube), and the chosen distribution for the parameters (triangular distribution)¹.

Figures 8.9 and 8.10 give the calculated mean and uncertainty range (based on the 2.5% and 97.5% percentiles) for the two output variables for both IPCC-1990 scenarios. Comparing the uncertainty ranges (the '95% confidence band' between the 2.5% and 97.5% percentiles) of both Figures clearly shows that the main uncertainties in the total source-effect chain arise in the last part of the IMAGE model (experimental version 1.6), when total radiative forcing is converted into global mean surface temperature

increase. This is supported by the following numbers: the relative uncertainty for the radiative forcing over the period 2050-2100 is around 10-12% for the BaU90 scenario, and 15-25% for the AP90 scenario (compared to relative uncertainty of 10-15% for CO_2 (main greenhouse gas) for both scenarios), whereas the relative uncertainty in the global mean temperature increase is 45-55% for the BaU90 scenario and 55% for the AP90 scenario. This is mainly caused by the uncertainty in the climate sensitivity parameter ([1.5,4.5]). The large range in the climate sensitivity parameter results from our lack of knowledge about the geophysical feedbacks within the climate system (see Chapter 4). The cumulation of uncertainties associated with radiative forcing due to the uncertainties in the concentrations of the other greenhouse gases cannot be assessed here, since this study only examines the uncertainties in the greenhouse gases CO_2 , CFC-11 and CFC-12.

As regards the temperature increase, an overlap area even exist between the projections of the BaU90 and AP90 scenario up to the end of the next century. Figures 8.11a and 8.11b present the relative frequency histogram for the global mean surface temperature increase for both IPCC-1990 scenarios for the year 2050, showing the overlap

¹ The mean value for globally averaged temperature is somewhat higher than the central estimate simulated with the IMAGE model, if all model parameters are set at their central value. This is a direct result of the assumed triangular distribution for the most important model parameter, the climate sensitivity parameter [1.5; 4.5], for which the statistical mean value is greater than the central value of 2.5°C , as adopted in the model.

Figure 8.9: Uncertainty in the total radiative forcing for the IPCC-1990 Business-as-Usual and Accelerated Policies scenario (uncertainty range represents the '95% confidence band' range between the 2.5% and 97.5% percentiles).

between the temperature projections for both scenarios during the mid-term period which ends in 2050.

8.6 Discussion and conclusions

The foregoing sensitivity and uncertainty analysis on the integrated model IMAGE (experimental version 1.6) addresses two basic questions: (i) what is the total cumulative uncertainty in the model outcome due to the uncertainties in the selected model para-

meters of the various separate submodels? (ii) what is the contribution of the individual model parameters and interacting model parameters to the total uncertainty?

For this purpose, this study makes use of the software package UNCSAM for performing uncertainty and sensitivity analyses, which is based on Monte Carlo techniques in combination with linear regression and correlation analysis. UNCSAM has the advantage of being able to address both questions, since it calculates the total sensitivity and/or uncertainty in the model outcomes, as well

Figure 8.10: Uncertainty of the global mean surface temperature increase for the IPCC-1990 Business-as-Usual and Accelerated Policies scenario (uncertainty range represents the '95% confidence band' range between the 2.5% and 97.5% percentiles).

Figure 8.11a: Frequency histogram for the temperature increase for the IPCC-1990 Business-as-Usual scenario assuming all chosen model parameters triangularly distributed for the year 2050 (uncertainty range represents the '95% confidence band' range between the 2.5% and 97.5% percentiles).

as the individual contributions of the various parameters to the time dependent total uncertainty over the entire simulation period. However, UNCSAM relies on the fact that the model parameters can be described by probability distributions (Monte Carlo-based methods), and therefore the analysis depends on the choices of these distributions (which are usually virtually unknown). Since these choices and specifications can be rather subjective and arbitrary, it is important to check the robustness of the results with respect to these choices. A disadvantage of UNCSAM is that with the implemented linear regression analysis the individual contribution of interacting parameters to the total uncertainty cannot be adequately determined in situations in which a linear regression models yields an inadequate fit. Therefore, in

order to answer question (ii), also the methodology of metamodelling was applied in combination with Monte Carlo sampling, so that the role of higher order effects (interactions and quadratic terms) in the total uncertainty can indeed be studied. Unfortunately, this approach to the construction of a meta-model is rather time consuming, as well as requiring sufficient knowledge of the model and its important model parameters (and interacting parameters). Therefore, in this study it was neither feasible to calculate the contributions of the model parameters to total uncertainty in a range of model outcomes, nor how this change in time and depends on the emission scenario.

For the carbon cycle model, the technique of metamodelling in combination with Monte Carlo sampling (assuming that all

Figure 8.11b: Frequency histogram for the temperature increase for the IPCC-1990 Accelerated Policies scenario assuming all chosen model parameters triangularly distributed for the year 2050 (uncertainty range represents the '95% confidence band' range between the 2.5% and 97.5% percentiles).

selected model parameters have triangular distributions) was been applied for question (ii), since it was expected that the interacting parameters would contribute to the total uncertainty in the model-outcome. Notwithstanding, a linear metamodel (without higher order effects) was found to be adequate for the output variable: atmospheric CO₂ concentration in 2100 for the BaU90 scenario. To check whether the chosen distribution function for the selected model parameters influence the metamodel constructed, a robustness study was performed with a less centred distribution, i.e. the uniform distribution, for all parameters. It was again found that the linear metamodel was valid. Based on this metamodel, it turned out that the fertilization factor, and the temperature terrestrial feedback parameters largely influence the atmospheric CO₂ concentration, which was to be expected since these factors directly influence the net primary production process, the main flow of carbon dioxide between the atmosphere and the terrestrial biosphere. In general, this metamodel shows that the terrestrial parameters (such as the humification factor of grass land, the residence time of humus in grass land, shift from temperate forest to agricultural land etc.) dominate the ocean parameters; only one ocean parameter being found among the ten most important parameters. For an answer to question (i), UNCSAM was used for the evaluation of the (time-dependent) total uncertainty in atmospheric CO₂ concentration for the BaU90 and AP90 scenarios. The relative uncertainty increases in time for both scenarios up to about 13% for the BaU90 scenario and about 12% for the AP90 scenario by 2100, depending on the CO₂ concentration.

For the halocarbon model, three output variables were selected: the CFC-11, CFC-12 and chlorine concentration as envisaged in the London Amendments and the Montreal Protocol. The analysis for both

questions was once again performed using UNCSAM, since no high order effects were expected, as was established by the analysis. The linear regression model obtained showed that for the three output variables, the atmospheric lifetime of CFC-11 and CFC-12 play an important role in the total uncertainty, especially after the phase-out date. However, in general the uncertainties about future atmospheric chlorine concentration are rather minor for both policies, less than 10%.

For the integrated IMAGE model (experimental version 1.6) as a whole, the total uncertainty only was evaluated using UNCSAM (to answer question (i)). Interacting parameters (such as the interaction between the temperature feedback parameters and climate sensitivity) are almost certainly contributors to the total uncertainty. Since there was insufficient time to construct a metamodel, the contributions of the individual sources to the total uncertainty were not assessed. Two output variables were here chosen, namely: radiative forcing and the surface temperature increase for the BaU90 and AP90 scenarios. The relative uncertainty for the radiative forcing over the period 2050-2100 is around 10-12% under the BaU90 scenario, and 15-25% under the AP90 scenario, whereas in the case of the temperature increase, relative uncertainty is 45-55% for the BaU90 scenario and 55% for the AP90 scenario. This emphasizes the fact that the main uncertainties occur in the last submodel of the integrated model, namely the climate model, i.e. in the conversion of the radiative forcing into temperature increase, and is mainly caused by the uncertainty in the climate sensitivity parameter ([1.5,4.5]). The large overlap area in the temperature projections for both scenarios shows that considerable uncertainty currently still persists, and that our knowledge of the phenomenon of climate change is far from complete.

Part IV Risk assesement: a target-oriented approach

9 Introduction

9.1 Background

During the last two decades, stratospheric ozone depletion and climate change have become major scientific and political issues. As regards the ozone issue, a series of successively updated international policies was reached: the Montreal Protocol (1978), the London Amendments (to the Montreal Protocol) (1990), and the Copenhagen Amendments (1992). The latter protocol strictly regulates the consumption of ozone depleting chemicals, in anticipating of a phase-out of currently used halocarbons by 1996, and of alternatives HCFCs by 2020.

In contrast, climate change is still in the stage of policy debate, and occupied a prominent position on the political agenda of the United Nations Conference for Environment and Development (UNCED) at Rio de Janeiro in 1992. The policy debate is shaped by two diametrically opposed viewpoints (Krause *et al.*, 1989):

- *Don't act until you are certain or wait-and-see (mainly adaptive strategies)*: those holding this view believe that there are still too many, and too large-scale, scientific uncertainties about the impacts of climate change - when, where and how it occurs, to justify strict emission constraints for greenhouse gases. Instead, more research should be conducted to reduce those scientific uncertainties.
- *Act now to minimize risks (mainly preventive or abatement strategies)*: those holding this view believe that the risks of climate change would be too high if the hypothesis should be borne out, that inaction have catastrophic consequences, and that irreversible processes cannot be halted. Society should therefore make investments and pursue policies to minimize such risks.

At present, the wait-and-see approach still predominates above the risk minimization view, a fact best illustrated by the final outcome of UNCED; a Framework on Climate Change Convention calling for a stabilization of the greenhouse gas concentrations in the atmosphere, but does not exactly specify when, and at which level concentrations of greenhouse gases should be stabilized, or what the implementations would be for global emissions. This declaration of intent is presently signed by all key countries.

The main argument that global warming and other undesirable consequences are not at all certain, and that man should therefore delay the adoption of an international response strategy, seems somewhat peculiar, if we bear in mind that most policy decision-making at high levels of government occurs under significant uncertainties. In fact, the ozone depletion problem is an outstanding example of policy making in the face of large-scale uncertainties. At the time of the first policy initiative, i.e. the Montreal Protocol of 1987, knowledge about the ozone depletion problem was far from complete, a fact mainly due to the inadequate understanding of the ozone depleting mechanisms. In this perspective, a comparison between the stages of policy making for the climate change problem now, and for the ozone depletion problem at the time of the Montreal Protocol, shows that the present status of scientific understanding of the climate change issue (see Part III) cannot be the main obstacle to an international agreement about the adoption of an abatement or preventive strategy in anticipation of climate change, and that the real stumbling-block is the economic costs of such a strategy. The present wait-and-see policy adopted vis-à-vis climate change fails

to appreciate incurring risks of possible catastrophic consequences is a strategy which carries its own costs. This approach only considers the high costs of preventive actions, while the risk-reducing benefits of such actions are discounted, and seen as uncertain.

On the other hand, the risk-minimization approach to climate change recognizes the limits of scientific certainty of this problem, and its advocates believe that, in view of the many delay mechanisms inherent in the climate system, each year of research or monitoring without preventive action will increment future global warming (Krause *et al.*, 1989). In fact, a complete understanding of the climate system will not be achieved until we are already confronted with the consequences of climate change. In the risk-minimization approach the risk-based costs also contribute to the real costs, and these costs are expressed as: *(probability of negative consequences)*(costs of negative consequences) = (major risk to society)*. This method of assessing risks is applied to a large range of problems, including most existing environmental problems to which traditional cost/benefit analysis is not fully applicable. However, for both problems of climate change and stratospheric ozone depletion neither cost/benefit analysis, or risk-based cost analysis, can be applied, because of the many uncertainties in estimating the costs of negative consequences.

9.2 Risk assessment: methodology

Part IV introduces a methodology for assessing the future risks involved in strategies for tackling environmental problems using long-term targets. These targets represent certain levels of indicators for environmental problems (such as temperature rise for climate change), which should be aimed at in future in order to limit the impacts and risks associated with the problem to acceptable levels. If these targets are not met, risks of negative consequences due to environmental change increase rapidly to high levels. Such risk evaluation can be associated with the concept of sustainable

development. In the present context, a policy is deemed to be less sustainable, or unsustainable, if the anticipated indicator exceeds the targets (sustainability targets). A future in which these targets are met is sustainable in the sense that the targets reflect a world in which the anticipated risks of environmental change tend to acceptable levels. One of the problems which arises, however, is the fact that a policy may be sustainable in terms of one issue (such as stratospheric ozone depletion), but not for another (climate change). This problem will be discussed in this section.

In its approach to climate change, AGGG's Working Group II has derived several quantitative climate targets from maximum tolerable rates at which ecosystems can adapt to changes in temperature, precipitation and sea level patterns, using data based on our understanding of the vulnerability of ecosystems, such as forests, coral reefs and natural wetlands, to historical temperature and sea level rises (AGGG, 1990c). Failure to meet these targets is expected to result in damage to these vulnerable ecosystems. These targets are defined by limits to rates of change and/or absolute levels of the main climate indicators, namely: mean temperature rise and sea level rise. Other impact indicators and targets have also been included, an example of such an indicator being the flooding frequency of the Dutch coastal defence system, whereby the target is the present safety norm ('Delta norm'), as defined by the Dutch Rijkswaterstaat (Delta Commission, 1960). Alternative different climate strategies are now being evaluated from the risk perspective by coupling these long-term climate and impact targets to the scenarios. In addition, the methodology is used for developing preventive emissions scenarios (risk-minimization approach), which comply with the climate targets, and thus limit the risks of global warming to a tolerable minimum.

In the case of the ozone depletion issue, several targets have been formulated in the past. The 1991 WMO Scientific Assessment report (Prather *et al.*, 1992) defined two main ozone targets, based on historical absolute

levels for atmospheric chlorine concentration. Firstly, the chlorine level of the middle-eighties, when ozone depletion was first observed at middle latitudes in spring and summer, and secondly, the chlorine abundance in the late 1970s when the Antarctic ozone hole as well as the accelerated negative ozone trends in the Northern Hemisphere started. The second ozone target is currently seen as the sustainable target. Provisional impact targets are also introduced here: targets pertaining to the risks of skin cancer incidence due to ozone depletion, based on existing health targets for ionized radiation as defined by VROM (1992). Again, the same methodology involving linking targets with scenarios has been used here for assessing the risks associated with a wide range of halocarbon policies (including the present Copenhagen Amendments policy).

Brief description of Part IV

The structure of Part IV is as follows. Chapter 10 assesses the ozone depletion implications of various halocarbon production and consumption policies with regard to the ozone targets as defined by WMO. Based on the findings in this analysis, additional preventive actions are finally formulated, which supplement the international actions which have already adopted and are described in the Copenhagen Amendments. This could bring forward the time scheduling of the sustainable ozone targets. This analysis has been conducted using the IMAGE halocarbon model, which will be described in this Chapter. In Chapter 11, the IMAGE model (experimental version 1.6) is used for analysing long-term climate strategies, i.e. the IPCC-1990 scenarios and also the updated

IPCC-1992 scenarios, in terms of their implications for temperature increase and sea level rise, and finally evaluated from the sustainability and/or risk perspective of the climate targets set by the AGGG. We also demonstrate how IMAGE (experimental version 1.6) can be used to develop a scenario, known-as the Low-Risk scenario, that meets the sustainable climate change targets. In this Chapter a delayed response analysis is also presented to show that the timing of the response is of crucial importance, and that the present wait-and-see policy may have major disadvantages. In Chapter 12, the impact of sea level rise on the frequency of floods overtopping the Dutch coastal defence system is assessed using the socio-economic-impact model. Furthermore, a classical risk-based cost minimization approach is presented for calculating the optimal economic safety-level (theoretical flooding frequency), and the related optimal height of the Dutch dikes. In Chapter 13, the health impact of ozone depletion, i.e. the increase in risks of skin cancer incidence in the Netherlands and the United States due to ozone depletion is assessed, using the UV-B impact model which is described in this section. In this assessment the human health risk targets used are those formulated by VROM (1992) for ionized radiation. As a follow-up to the risk analysis for different climate strategies, Chapter 14 presents for the climate scenarios, namely: IPCC-1990 scenarios, as well as the Low-Risk scenario, an approach for allocating future emissions of CO₂ among regions, based on an equity rule, by which all past and future inhabitants on the Earth are permitted to emit an equal CO₂ quatum per year. The resulting initial allocation of emissions may be used as a start for a concept of tradeable emission rights.

10 Accelerated phase-out of CFCs: does it reduce the ozone and climate risks?

This Chapter is partly based on: Elzen, M.G.J. den, Swart, R.J., and Rotmans, J. (1992b): Strengthening the Montreal Protocol: does it cool down the greenhouse? The Science of the Total Environment 113, 229-250.

10.1 Introduction

As a result of global concern about ozone depletion resulting from the use of chlorofluorocarbons (CFCs) and other halocarbons, a concern first triggered by the discovery of the Antarctic ozone hole in 1987, 24 nations, including the United States, Japan, the Soviet Union and the members of the European Community signed the Montreal Protocol (UNEP, 1987). This international environmental agreement limited the consumption^[1] of specified CFCs, namely: CFC-11, CFC-12, CFC-113, CFC-114 and CFC-115, to 50% of 1986 levels by the year 1998. The consumption of certain halons, namely: halon-1211, halon-1301 and halon-2402, were to be restricted to 1986 levels starting by 1992. In the light of increasing scientific and public concern about ozone depletion, confirmation that CFCs and other ozone depleting substances were major factor in creating the Antarctic ozone hole, observations of significant ozone decreases in both the Northern and Southern Hemispheres at middle and high latitudes (Stolarski *et al.*, 1991; WMO, 1990, 1992), in 1990, 93 nations agreed to adjust and amend the Montreal Protocol, thus creating the London Amendments (UNEP, 1990). The control measures set out in the London Amendments provide for the phasing-out of the consumption of CFCs, halons and carbon tetrachloride (CCl₄), by the year 2000, and methylchloroform (CH₃CCl₃) by 2005 (base year for CCl₄ and CH₃CCl₃: 1989). In 1992, NASA observa-

tions showed alarming high chlorine levels over large parts of middle and high latitudes of the Northern Hemisphere, which could independently induce further stratospheric ozone losses (NASA, 1992). In 1992 in Copenhagen, and thus as an immediate response, an international agreement was adopted to phase out all of the regulated halocarbons as early as 1996 (and all of the halons by 1994). The consumption of methyl bromide is stabilized at the 1991-levels by 1996. As regard the alternatives HCFCs, a maximum level of consumption (calculated in Ozone Depletion Potential or ODP tonnes) was adopted, equal to the sum of calculated 1989 consumption of HCFCs and 3% of calculated 1989 consumption of CFCs. The phasing-out of the alternatives would then proceed in three steps, with a 35% reduction of the maximum HCFC consumption level by 2005, a 65% reduction by 2010, a 90% by 2015, and finally a total phase-out by 2020.

A further negative environmental impact of halocarbons is their contribution to climate change, due to their radiative properties (Ramanathan *et al.*, 1985). New findings published by Ramaswamy *et al.* (1992) and the WMO (1992) indicate significant indirect radiative effects of halocarbons caused by the negative radiative impact from lower stratospheric ozone losses in middle to higher latitudes over the last decade. In the middle latitudes, the magnitude of negative ozone forcing approaches, and can even exceed, the positive direct radiative forcing associated with CFCs in the troposphere. In the higher latitudes, negative ozone forcing can counteract a fraction of the total non-ozone forcing.

The main goal of this Chapter is to assess the stratospheric ozone and climate change

^[1]The Montreal Protocol and the London Amendments define consumption as production plus imports minus exports and therefore does not limit the use of recycled material. This definition of consumption is used throughout the whole Chapter.

implications of a range of policies for future production of currently used halocarbons and their possible alternatives. This evaluation has been performed from a risk perspective by relating the halocarbon production scenario with the long-term ozone targets as defined by the WMO (1992) and a halocarbon-climate target as formulated here. The currently-used halocarbons include the chlorinated chemicals: CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, CCl_4 , CH_2Cl_2 and HCFC-22, and the brominated chemicals: halon-1211, halon-1301 and halon-2402. Most previous studies have assessed one of the two environmental effects. Estimating future atmospheric chlorine and bromine, and corresponding ozone changes for various emission scenarios has been performed using atmospheric chemistry transport models (Fisher *et al.*, 1990a; WMO, 1990a). These projections were recently updated by Prather *et al.* (1992) in the WMO 1992 Scientific Assessment report based on new emission scenarios and calculations of major advanced stratospheric chemistry models, incorporating currently-known heterogeneous processes associated with sulphate aerosols. Alternatively, Prather and Watson (1990) had used a simple numerical model for calculating the future chlorine and bromine levels implied by various halocarbon production scenarios. An updated version of this model (present data concerning atmospheric lifetimes of compounds, concentrations and emissions of the halocarbons) was also used in the analysis published by Prather *et al.* (1992). With respect to climate change, various studies have estimated the radiative effects of halocarbons using radiative transfer models (Ramanathan *et al.*, 1985; Hansen *et al.*, 1988). Based on these studies, simple expressions have been derived for the relationships between the concentration and the radiative forcing of trace gases (including halocarbons) (Wigley, 1987; Hanssen *et al.*, 1988; Fisher *et al.*, 1990b), as presented in Houghton *et al.* (1990). Using these relationships, a previous study (den Elzen *et al.*, 1992b) assessed the radiative implications of various halocarbon production strategies. The indirect radiative effects of halocarbons, which may well, to some extent, counteract

the direct radiative effects, were not taken into account in that study.

This Chapter evaluates various strategies for the currently used halocarbons and some of the future alternatives with respect to future atmospheric chlorine (Cl) levels (main cause of the ozone depletion), as well as the radiative forcing from halocarbons, including the direct and indirect radiative effects. For a subset of scenarios concerned with emissions of the brominated chemicals (halons) the implications of future bromine levels are also examined. In this study, a simple numerical halocarbon model, which is a separate IMAGE module (experimental version 1.6) is used, which will be described in detail here. In complexity, this model is comparable to the model used by Prather *et al.* (1992) with the exception of: (1) the production and consumption of halocarbons is disaggregated into nine regions: the USA, the EC, Japan, other OECD countries, Eastern Europe, the GOS, China, India and other (developing) countries; (2) the delay between halocarbon production and emission are regarded as dependent on the end-use category, as stated in Wigley (1988); (3) the implemented direct radiative forcing-atmospheric concentration relationships are incorporated; and (4) an implementation of the relationship between the indirect radiative effects and the atmospheric chlorine concentrations which follows Wigley and Raper (1992) is included.

The structure of this Chapter is as follows. After first describing the halocarbons (section 10.2), in the next two sections the role of halocarbons in stratospheric ozone depletion and climate change is described (section 10.3 and 10.4). The halocarbon model is then described in section 10.5. In section 10.6, the results of the model-calculations concerning future atmospheric chlorine and bromine levels and direct radiative forcing are presented and evaluated with regard to the ozone targets as identified by the WMO (1992) and with regard to a halocarbon-climate target as introduced for the London Amendments as well as for various policies (including the IPCC-1990 scenarios).

10.2 Halocarbons

The halocarbons can be split into two groups. The fully halogenated halocarbons containing chlorine and/or bromine, fluorine and carbon, such as the chlorofluorocarbons or CFCs, CCl_4 and halons, have a long atmospheric lifetime. They are primarily removed by photodissociation by UV radiation in the stratosphere, which is attended by the release of highly reactive chlorine (Cl_x) or bromine (Br_x). The other halocarbons, i.e. the non-fully halogenated group, differ in that they contain a hydrogen atom in addition to the halogen elements and carbon, e.g. CH_3CCl_3 , methyl chloride (CH_3Cl), and a number of hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs). These compounds have much shorter atmospheric lifetimes than the CFCs, because of their decomposition in the troposphere by reaction with OH. The atmospheric concentrations of the fully halogenated halocarbons are steadily increasing. Since the fully halogenated halocarbons are not removed in the troposphere, these trace gases are distributed almost uniformly over the globe (the concentration in the Northern Hemisphere is slightly higher than in the Southern Hemisphere, which is consistent with the geographical distribution of emissions). Because of their tropospheric removal, the

concentrations of non-fully halogenated halocarbons, however, exhibit regional differences of 10-20% (Fraser *et al.*, 1992). Table 10.1 charts the globally averaged atmospheric lifetimes, the atmospheric concentrations and the trends of the major halocarbons use in 1990.

10.2.1 Fully halogenated halocarbons

chlorofluorocarbons (CFCs)

The historical production data (1931-1989) of the most important chlorofluorocarbons, CFC-11 and CFC-12, are reported by the Chemical Manufacturers Association (CMA), and are based on the production figures submitted by CFC-producing companies to the CMA (CMA, 1990; 1987). CFC-11 and CFC-12 are produced for four categories of end-use: aerosols, open cell foams and other applications, closed cell foams, and hermetically and non-hermetically sealed refrigerators (Gamlen *et al.* (1986). In Figures 10.1a and 10.1b the historical production statistics of CFC-11 (from 1931) and CFC-12 (from 1939) for companies reporting to the CMA are given up to the year 1989. The 1986-production of CFC-11 and CFC-12 by the CMA companies was about 380 and 330 kilotons (kt), respectively, which is about 90% (421 kt) and about 75% (451 kt) of the 1986-world-wide CFC-11 and CFC-12 pro-

Figure 10.1a: CFC-11 production in the different end-use categories for the CMA-reporting countries till 1989 (CMA, 1989).

Table 10.1: General characteristics of the major halocarbons

Halocarbon	Lifetime ¹ (years)	Production 1991 ² (kton/year)	Concen- tration 1990 ³ (pptv)	Trend 1989 ³ (pptv/yr)	Direct radiative forcing ⁵ (Wm ⁻² /ppbv)	chlorine/ bromine change ⁶ (ppbv Cl _x -Br _x /ppbv)
CFC-11 (CCl ₃ F)	55	263	254-277	9-10	0.22 ⁶	2.95
CFC-12 (CCl ₂ F ₂)	116	259	470	17-18	0.28 ⁶	1.80
CFC-113 (C ₂ Cl ₃ F ₃)	110	143	69	5-6	0.28	2.85
CFC-114 (C ₂ Cl ₂ F ₄)	220	5	16-21	~1	0.32	1.80
CFC-115 (C ₂ ClF ₅)	550	11	5		0.26	0.95
Carbon tetrachloride (CCl ₄)	47	80 ⁸	108	1-1.5	0.10	3.90
Methylchloroform (CH ₃ CCl ₃)	5.5 ³ -6.1 ⁸	605 ⁸	140	4.8-5.1	0.05	2.95
Methyl chloride (CH ₃ Cl)	1.5 ⁴	600			0.99	
Chloroform (CHCl ₃)		~10				
HCFC-22 (CHClF ₂)	15.8	220 [*]	115	5-6	0.19	0.60
HCFC-123 (C ₂ HCl ₂ F ₃)	1.7				0.18	
HCFC-124 (C ₂ HClF ₄)	6.9				0.19	
HFC-125 (C ₂ HF ₅)	40.7				0.24	
HFC-134a (C ₂ H ₂ F ₄)	15.7				0.17	
HCFC-141b (C ₂ H ₃ Cl ₂ F)	10.8				0.14	
HCFC-142b (C ₂ H ₃ ClF ₂)	22.4				0.18	
HFC-143a (C ₂ H ₃ F ₃)	64.6				0.14	
HFC-152a (C ₂ H ₄ F ₂)	1.8				0.12	
HCFC-225ca (C ₃ HCl ₂ F ₅)	2.8					
HCFC-225cb (C ₃ HCl ₂ F ₄)	8.0					
halon-1211 (CBrClF ₂)	11 ⁸	11	2.3-4.0	0.4-0.7		0.00095
halon-1301 (CBrF ₃)	77 ⁸	10 [*]	1.9-2.8	0.2-0.4	0.2 ⁸	0.00095
methyl bromide (CH ₃ Br)	1.6 ⁸		10-15	?		0.00098

* Based on the model calculations (see section 10.5)

¹WMO (1992) and IPCC (1992); ²UNEP (1991a); ³the 1990 atmospheric concentration have been estimated by reference to an extrapolation of the measurements in 1989 given by Fraser *et al.* (1992), assuming that the recent trends remain approximately constant; ⁴Prather and Watson (1990); ⁵Fisher *et al.* (1990b), except CF₃Br based on Ramanathan *et al.* (1985), based on Shine *et al.* (1990); ⁶stratospheric chlorine (Cl_y) and bromine (Br_y) according to Prather *et al.* (1988); ⁷Hansen *et al.* (1988); and ⁸Prather *et al.* (1992).

duction estimates of UNEP (1991a). The world-wide production of CFC-11 and CFC-12 in 1991 was 63% and 59% of the 1986 level respectively (UNEP, 1991a). The present production of the other regulated CFCs is 59% (CFC-113), 30% (CFC-114), and 85% (CFC-115) of the 1986 levels,

respectively (UNEP, 1991a). These CFCs are used in aerosols (CFC-113, CFC-114), foams (CFC-113, CFC-114), refrigerants (CFC-114, CFC-115), solvents (CFC-113) and others. In Figure 10.2 the use of all controlled CFCs (including CFC-11 and CFC-12) across the various applications is given for

Figure 10.1b: CFC-12 production in the different end-use categories for the CMA-reporting countries till 1989 (CMA, 1989).

the base year 1986 and 1991 (UNEP, 1991a). The total CFC market in 1991 was 60% of what it was in 1986, a rate at which CFC consumption will have fallen by 50% in 1992, three years in advance of the requirements of the London Amendments. Reductions in the different applications have occurred in aerosols (58%), foams (35%), refrigerants (7%) and solvents (41%).

Production and consumption of CFCs will be further limited in future because reductions are mandatory under the London Amendments, and the recent international agreement as adopted in the Copenhagen Amendments (phase-out by 1996). UNEP (1991a) had already examined the feasibility of earlier phase-outs, and concluded that it is technically and economically feasible to phase-out all consumption of CFCs in all sectors (end-use categories) by 1995-1997 in the developed countries. In the field of refrigeration, a complete phase-out by 1997 will be attended by increased costs; and additional sufficient recycling and recovery measures will therefore be necessary. In the developing world, it is also technically and economically feasible to phase out CFCs in many sectors (foam, aerosols, etc.) before 1995, although such a rapid phase-out would depend on adequate financing and technical assistance. For the more specialized applications, the developed world needs extra time

(five to eight years). The complete 1997 phase-out is set out in Figure 10.2 (UNEP, 1991a). This Figure also shows the dependency of an earlier phase-out on the availability of HCFC and HFC replacements, which will be described in the next section.

carbon tetrachloride

The primary reported use of carbon tetrachloride (CCl_4) is still as a feedstock in the production of CFC-11 and CFC-12. However, increasing concentrations indicate that CCl_4 must still be being used in some countries of the world for non-feedstock applications, as a solvent in aerosol products, metal degreasing, dry cleaning, etc. It is possible to phase-out the use of CCl_4 in non-feedstock applications by the year 1995 (UNEP, 1991a).

halons

The major use of halons (halon-1211, halon-1301 and halon-2402) is as fire retardants. The total world production was about 25 kilotons in 1990, of which over 70% was stockpiled to provide stand-by fire protection (UNEP, 1991b). These quantities may appear to be small compared to CFC volumes, but the bromine atoms released from these sources into the atmosphere have considerable Ozone Depletion Potential (ODP). Moreover, the stocks held for fire protection (about 150 kt in 1990) form a potential environmental threat.

Figure 10.2: Usage of CFCs and HCFCs in different applications for the years 1986, 1991, and 1997 (1997 CFC phase-out) (UNEP, 1991a).

	CFC (A)	most likely HCFC(s) (B)
aerosols	CFC-11, -12, -113, -114	HCFC-22, -142b
foams	CFC-11, -12, -113, -114	HCFC-22, -123, -141b, -142b
refrigerations	CFC-11, -12, -114, -115	HCFC-22, -123, -124, -142b
solvents	CFC-113	HCFC-141b, -225
other	CFC's	HCFC's

According to UNEP (1991a), halon production can be phased out in 1995 if recycled halons are used for new applications. In order to minimize the environmental risk, it is desirable to manage the existing halon stocks by recovery (recycling), replacement by substitutes and destroying surplus quantities in an acceptable manner. However, human exposure to risks of fire and explosion should be considered in any decision to phase-out the halons.

10.2.2 Non-fully halogenated halocarbons

alternatives: HCFCs (hydrochlorofluorocarbons) and HFCs (hydrofluorocarbons)

As mentioned above, a more rapid phasing-out of the controlled substances depends on the availability of alternatives. The HCFCs and HFCs presently being considered as potential substitutes for the CFCs are: HCFC-22 (CHClF_2), HCFC-123 ($\text{C}_2\text{HCl}_2\text{F}_3$), HCFC-124 (C_2HClF_4), HFC-125 (C_2HF_5), HFC-134a ($\text{C}_2\text{H}_2\text{F}_4$), HCFC-141b ($\text{C}_2\text{H}_3\text{Cl}_2\text{F}$), HCFC-142b ($\text{C}_2\text{H}_3\text{ClF}_2$), HFC-143a ($\text{C}_2\text{H}_3\text{F}_3$), HFC-152a ($\text{C}_2\text{H}_4\text{F}_2$), HCFC-225ca ($\text{C}_3\text{HF}_5\text{Cl}_2$) and HCFC-225cb ($\text{C}_3\text{HF}_4\text{Cl}_2$). Only HCFC-22 is already being used on a large scale. Figure 10.2 shows the likely total production of the most promising HCFCs (containing chlorine) in 1997, and includes the assumed present HCFC-22 production of 220 kilotons. The other part of the total HCFC production in

1997 is due to replacement of CFC products. The assumed replacement fractions in the various sectors are: aerosols, 6% (5-8%); foams, 5%; refrigeration, 45%; and solvents, 34% (18-50%) (UNEP, 1991a). The remainder is to be replaced by alternative substances (HFCs), conservation, recycling and non-fluorocarbons, which are all non-ozone depleting solutions. For example, in the refrigeration sector, 45% is replaced by HFCs (such as HFC-134a, HFC-152a). In the near future, it will be technically possible to increase the replacement fraction by increased use of non-ozone depleting substances.

methylchloroform

The major application of this chemical is as a cleaning solvent (80%) (UNEP, 1991a). The remaining uses of methylchloroform are in aerosols, coatings and adhesive applications. The consumption of methylchloroform can be phased out by 1995 using alternative processes and substitutes, although worldwide technological cooperation would be required.

methyl chloride

Methyl chloride (CH_3Cl) is exclusively of natural origin, since it is primarily released from the oceans and during biomass burning. There are no indications that the atmospheric concentration of CH_3Cl from the present level of 0.6 ppbv is increasing (Fraser *et al.*, 1992).

chloroform and other halocarbons

In 1989, the global atmospheric concentration of chloroform (CHCl_3) was about 10 pptv. In order to account for this global concentration, we are inclined to assume that approximately 40% of the CHCl_3 source is anthropogenic (Khalil and Rasmussen, 1983a; 1983b). The present concentrations of other halocarbons are: CH_2Cl_2 (~35 pptv); CCl_2CCl_2 (~30 pptv); CH_2ClCHCl (~35 pptv) and CHClCCl_2 (~10 pptv) (Fraser *et al.*, 1992).

methyl bromide and other brominated species

Methyl bromide (CH_3Br) is the major source of atmospheric bromine (31%), and has both natural and anthropogenic sources. The major sources of methyl bromide are oceanic biological processes (mainly algal). The averaged concentration in the Northern and Southern Hemispheres is 15 pptv and 10 pptv, respectively. This suggests a local anthropogenic source of CH_3Br . Other brominated substances with the same sources are CH_2Br_2 , CHBr_3 , CH_2BrCl , and CHBrCl_2 , with atmospheric concentrations in 1989 of 2-3 pptv, 2-3 pptv, 1-2 pptv, and 1 pptv, respectively (Fraser *et al.*, 1992).

10.3 The role of halocarbons in ozone depletion

10.3.1 The present contribution to the atmospheric CIBr-levels

Since industrial production of CFCs started (CFC-11 in 1931, and CFC-12 in 1939), atmospheric chlorine (Cl) levels have increased from about 0.6 ppbv (traceable to the natural source of atmospheric chlorine, i.e. methyl chloride), to about 2 ppbv in the late 1970s when the Antarctic ozone hole started to become apparent (Farman *et al.*, 1985). In 1990, the level was about 3.9 ppbv (with a present annual rate of increase of 0.11 ppbv) (Fraser *et al.*, 1992). The man-made halocarbons comprise about 80% of the present atmospheric chlorine loading. The contribution of the major halocarbons to this anthropogenic atmospheric chlorine level is described in Figure 10.3a (Fraser *et*

al., 1992). Methyl chloride is the main source of natural atmospheric chlorine loading.

Bromine (present Br-level 40 pptv) also plays a role in stratospheric ozone depletion, since bromine is 30 to 120 times more effective per atom than chlorine in catalyzing ozone reactions (Prather *et al.*, 1992). The halons are the major anthropogenic sources of atmospheric bromine (halon-1211, 7%; halon-1301, 5%), although methyl bromide (CH_3Br) which has mainly natural sources, is the dominant source of bromine (31%).

10.3.2 Ozone Depletion Potentials (ODPs)

Recent, and earlier, regulatory policies for fully halogenated CFCs and other ozone depleting substances have been supported by reference to the policy index, the Ozone Depleting Potential (ODP), which quantifies the relative contribution of different halocarbon towards stratospheric ozone depletion.

The concept of ODP was first introduced by Wuebbles (1981; 1983), and was defined as the steady-state amount of stratospheric ozone destroyed by each unit of halocarbon X emitted per year (at a continuous release) into the atmosphere relative to that for a unit mass emission of CFC-11 according to the formula:

$$\text{ODP}(X) = \frac{dO_3(X)}{dO_3(\text{CFC-11})} \quad (10.1)$$

where $dO_3(X)$ is the total quantity of ozone destroyed at a steady-state per unit mass emission rate. This definition provides a relative measure of stratospheric ozone depletion compared to CFC-11. These steady-state ODPs have been calculated using atmospheric chemical models as presented by Fisher *et al.* (1990a) and the WMO (1990a; 1990b). Table 10.2 sets out the ODPs of CFCs, HCFCs, halons and other halocarbons according to the WMO (1990a). The most significant uncertainties in the ODP-calculations are illustrated by the fact that none of the models used here could simulate the chemical and dynamical processes causing the Antarctic ozone hole, and associated with the heterogenous chemistry of the lower

Figure 10.3a: Relative contribution by halo-carbons to the 1989 anthropogenic atmospheric chlorine concentration (Fraser *et al.*, 1992).

stratosphere. Although these atmospheric chemistry models are currently being improved by incorporating more accurate reaction rate coefficients, absorption cross sections and known heterogeneous processes related to sulphate aerosols, these models are still not yet able to simulate the ozone hole over Antarctica. By reference to these improved models, steady-state ODPs have been recalculated, as presented in the 1992 WMO scientific assessment report (Pyle *et al.*, 1992) and in Table 10.2. The numerical values are generally similar to the ODPs given by the WMO (1990a). Alternatively, Pyle *et al.* (1992) presented revised ODPs based on a new semi-empirical, observation-based method. This approach relies more on

atmospheric observations and less on model calculations in characterizing the polar ozone losses, and is therefore considered to be superior to the model approach (WMO, 1992) (see also Table 10.2). These alternative ODPs are generally higher for compounds with long stratospheric lifetimes relative to that of CFC-11 (e.g., HCFC-142b and HCFC-22 with stratospheric lifetimes of more than 200 years) and slightly lower for chemicals with shorter stratospheric lifetimes (e.g., CCl₄ and CH₃CCl₃ with stratospheric lifetimes of less than 55 years). These differences can be explained by the time-dependent breakup of these chemicals within the stratosphere relative to that of CFC-12.

Figure 10.3b: Relative contribution to the radiative forcing due to the increases in concentration for the greenhouse gases over the last decade 1980-1990 (Shine *et al.*, 1990).

Table 10.2: Policy Indices (ODP and GWP)

Halocarbon	Model ODP (WMO, 1990a)	Model ODP (Pyle <i>et al.</i> , 1992)	Semi-empirical ODP (Pyle <i>et al.</i> , 1992)	Model GWP (100 years) (Rotmans and den Elzen, 1992a)
CFC-11	1.0	1.0	1.0	4665
CFC-12	0.9-1.0	0.9-1.0	1.0	9168
CFC-113	0.8-0.9	0.9-1.0	1.07	5805
CFC-114	0.6-0.8	0.6-0.8	0.8	8850
CFC-115	0.3-0.5	0.3-0.5	0.5	9040
CCl ₄	1.0-1.2	1.0-1.2	1.08	1600
CH ₃ CCl ₃	0.1-0.16	0.1-0.15	0.12	131
HCFC-22	0.04-0.06	0.03-0.05	0.055	2142
HCFC-123	0.013-0.022	0.01-0.02	0.02	119
HCFC-124	0.016-0.024	0.02-0.035	0.022	570
HFC-125	0	0	0	4389
HFC-134a	0	0	0	1541
HCFC-141b	0.07-0.11	0.1-0.12	0.11	764
HCFC-142b	0.05-0.06	0.035-0.06	0.065	2348
HFC-143a	0	0	0	4996
HFC-152a	0	0	0	195
HCFC-225ca	-	0.015-0.02	0.025	-
HCFC-225cb	-	0.02-0.03	0.033	-
halon-1211	3.0	1.8-5.0	4	-
halon-1301	10.0	10.0-12.5	16	6240
CH ₃ Br	-	0.5-0.7	0.6	-

10.4 The role of halocarbons in climate change

10.4.1 The present contribution of halocarbons to radiative forcing

Besides having damaging effects on stratospheric ozone, halocarbons are also important greenhouse gases. Shine *et al.* (1990) estimated the relative role of these gases in climate change and found that their contribution to the total radiative forcing associated with all greenhouse gases over the period 1765-1990, was 12%. Since the atmospheric concentrations of the halocarbons are currently increasing more rapidly than the other greenhouse gases, their contribution to total radiative forcing over the last decade (1980-1990) is much greater, about 24% (Figure 10.3b) (Shine *et al.*, 1990).

However, the role of halocarbons in the

anticipated climate change has recently been called into question in view of their indirect radiative effects on the climate system through their interaction with stratospheric ozone depletion (Ramaswamy *et al.*, 1992). Based on slightly different assumptions about the vertical profile of the lower stratospheric ozone losses over the last decade, two radiative transfer modelling studies (Ramaswamy *et al.*, 1992; WMO, 1992), indicate significant indirect radiative effects of halocarbons caused by the negative radiative impact from lower stratospheric ozone losses in middle to higher latitudes over the last decade. In the middle latitudes, the magnitude of the negative ozone forcing approaches, and can even exceed, the positive direct radiative forcing associated with the eight halocarbons considered (CFC-11, CFC-12, CFC-113, CFC-114, CFC-115, CCl₄, CH₃CCl₃, and HCFC-22) in the tropo-

sphere. In the higher latitudes, negative ozone forcing can counteract a fraction of the total non-ozone forcing associated with all greenhouse gases.

Globally and annually averaged ozone forcing sets off 80% of the total, direct, global-mean radiative forcing caused by the halocarbons under consideration. It should be emphasized that these calculated regional ozone forcing magnitudes are extremely sensitive to the altitude at which ozone losses are occurring (Ramanathan *et al.*, 1985), and the exact ozone profile and ozone trend below 17 km are still especially uncertain factors. The globally averaged result should be treated with even more caution, since the spatial dependence of ozone losses implies that this result must be a considerable simplification (WMO, 1992).

10.4.2 Global Warming Potentials (GWPs)

The direct GWPs for various time horizons have been calculated by IPCC (1992), and, in addition, have also been calculated using the IMAGE model (version 1.6) (Rotmans and den Elzen, 1992a). These GWPs are set out in Table 10.2.

10.5 Methodology

In order to calculate the stratospheric ozone and climate change implications of various halocarbon policies, the halocarbon model was developed at the RIVM. This model is designed to simulate the atmospheric chlorine and bromine concentration, as well as radiative forcing due to halocarbons, using a 200-year simulation run, from 1900 to 2100. In order to reach this objective, the halocarbon model integrates the various subsystems involved into a synthetic framework. Figure 10.4 shows the system diagram of the halocarbon model based on the compartment/reservoir system perspective (see section 3.2.2, Chapter 3), consisting of the following subsystems: the CFC-industry, CFC-consumption, landfill sites, the atmosphere (troposphere and stratosphere) and the Earth's surface. Each of the subsystems describes a separate scientific aspect of the problem, and is

represented by a set of state variables (denoted by the *s.index* in the Figure). The key variables of the five subsystems are: halocarbon production, halocarbon consumption, storage of halocarbons, atmospheric concentrations and equilibrium surface temperature increases. The subsystems are coupled by processes, thereby illustrating the major interactions between the state variables. Here the following processes (denoted by the *pr.index*) can be distinguished: transport, consumption, recycling, emissions, stratospheric transport and radiative perturbations, respectively. Processes such as atmospheric chemical processes can also be distinguished within the atmosphere subsystem. During a simulation run, in each iteration the next state of the system, described by the state variables, is computed as a function of these derived time dependent relationships and the present state (see section 3.3)

10.5.1 Model description

In this section, the system diagram for the halocarbon model is discussed in more detail, and a model description of each subsystem with its state variables and processes is given. The driving force of the whole system is the man-made production of the halocarbons in the subsystem which is the CFC-industry. In this section, the state variables are mathematically denoted by A , and the processes by $A^{\rightarrow}$, while parameters or state variables which are scenario dependent, are denoted as A^* or a^* .

The CFC-industry

The halocarbon model considers the following halocarbons: five CFCs (CFC-11, CFC-12, CFC-113, CFC-114, CFC-115), CCl_4 , CH_3CCl_3 , HCFC-22, three imaginary substitutes (HCFC-X, HCFC-Y and HFC-Z), and two halons (halon-1211, halon-1301), as well as CH_3Cl and CH_3Br . In the calculations, it is assumed that the natural source of atmospheric chlorine, CH_3Cl , remains constant in the model at 600 pptv. Similarly, the atmospheric concentration of methyl bromide (CH_3Br), the dominant source of atmospheric bromine, is assumed to remain constant at 15 pptv, since there is no adequate

Figure 10.4: Systems diagram of the halocarbon model

knowledge of its emission. Three imaginary compounds are chosen to represent a class of alternatives (H(C)FCs): HCFC-X, represent the class of HCFCs with an ODP greater than 0.05 (HCFC-141b, HCFC-142b);

HCFC-Y, the class of HCFCs with an ODP lower than 0.05 (HCFC-123, HCFC-124, HCFC-225); and HFC-Z the class with an ODP of zero, the HFCs (HFC-125, HFC-134a, HFC-143a, HFC-152a). These classes

Table 10.3: General characteristics of the three imaginary compounds

Com- pound	Lifetime (years)	tropospheric lifetime (years)	stratospheric lifetime (years)	ODP	number of chlorine atoms	direct radiative forcing ($\text{Wm}^{-2}/\text{pptv}$)	GWP 100 years	Factor (kt.pptv^{-1})
HCFC-X	15	20	150	0.1	1	0.18	1500	22.0
HCFC-Y	5	5.1	75	0.03	1	0.18	500	22.0
HFC-Z	30	30	infinite	0	0	0.18	3000	22.0

are representative in the sense that they have the average properties of these gases with respect to atmospheric lifetime (stratospheric and tropospheric lifetimes), number of chlorine atoms per molecule, ODP and GWP. The general characteristics of the three imaginary compounds are described in Table 10.3, and based on the WMO (1992) data.

The only state variable in the CFC-industry subsystem is the halocarbon production ($PC_{isr}(t)$). Here i ($=1, \dots, 13$) denotes the halocarbon ($i=1$: CFC-11; $i=2$: CFC-12; $i=3$: CFC-113; $i=4$: CFC-114; $i=5$: CFC-115; $i=6$: CCl_4 ; $i=7$: CH_3CCl_3 ; $i=8$: HCFC-22; $i=9$: HCFC-X; $i=10$: HCFC-Y; $i=11$: HFC-Z; $i=12$: halon-1211; $i=13$: halon-1301). Halocarbon production is disaggregated into six major end-use categories ($s=1, \dots, 6$) (Gamlen *et al.*, 1986), namely: aerosols and open cell foams ($s=1$), solvents ($s=2$), fire-extinguisher ($s=3$), closed cell foams ($s=4$), and hermetically sealed together with non-hermitically sealed refrigerators ($s=5, 6$). Furthermore, the model disaggregates halocarbon production into nine regions, namely: the USA, the EC, Japan, other OECD countries, Eastern Europe, the GOS, China, India and other (developing) countries, which are represented by $r=1, \dots, r=9$, respectively.

The total historical production of CFC-11 and CFC-12 by companies which reported to the CMA over the period 1931 to 1989 is based on CMA data (CMA, 1990). These data also feature subdivision into the six end-use categories. The uncertainties in the production data from countries reporting to the CMA are probably not greater than $\pm 0.5\%$ (Gamlen *et al.*, 1986). In the case of other

countries (companies which produce CFCs, but do not report to the CMA, such as the USSR, China, India and Argentina) the degree of uncertainty is much greater. According to Gamlen *et al.* (1986), this causes an uncertainty factor in cumulative release figures for all CFC producing countries of the order of 4% for CFC-11 and 2.8% for CFC-12. In the case of the non-reporting countries, the only distinction made is that between aerosols and non-aerosols. The historical production of the non-reporting countries is estimated for the period 1965-1975 based on CMA (1990), while for the period 1975-1986 an annual growth of about 19% for CFC-11 and about 5% for CFC-12 is assumed, these percentages being based on the best estimate of world production of CFC-11 and CFC-12 in 1986 according to UNEP (1991a). Over the period 1986-1991, a similar growth rate is assumed where the non-reporting countries are concerned. World production of CFC-11 and CFC-12 in 1991 is based UNEP's (1991a) best estimate of 263 kt and 159 kt, respectively.

The historical production data of CFC-113 is based on GEMS (1989) for the period 1960-1975, and over the period 1975-1986 an annual 15% growth was assumed to match with UNEP's (1991a) central estimate of 241 kt in 1986. For CFC-114 and CFC-115, a linear increase in the production has been assumed over the period 1960-1986, based on UNEP's 1986 estimates (UNEP, 1991a). The historical production figures for CH_3CCl_3 and CCl_4 over the period 1930 till 1980 are based on GEMS (1989), and for the

period 1980-1991 on Prather *et al.* (1992). The historical production of HCFC-22 and both halons are determined by running the halocarbon model in an inverse mode, and using as input the historical concentration data given by Fraser *et al.* (1992) for HCFC-22, and by the WMO (1990a) for both halons. The historical production of the imaginary substitutes equals zero.

The production of the regulated halocarbons for the period 1991 to 2100 is presumed to follow a scenario, based on assumptions about the participation of the developed and developing world to the Copenhagen Amendments, the future consumption pattern of the non-participating countries, and future recycling and recovery practices. The state variable for halocarbon production ($PC_{isr}(t)$) over the period 1991 to 2100 is described as:

$$PC_{isr}(t) = [PC_{isr}^*(t) - RC_{isr}^{\rightarrow}(t)]$$

$$i=1,...,5,12,13 \quad s=5,6 \quad \forall r$$

$$PC_{isr}(t) = PC_{isr}^*(t) \quad (10.2)$$

$$i=1,...,5,12,13 \quad s=1,...,4 \quad \forall r$$

$$i=6,7 \quad \forall s \quad \forall r$$

where $PC_{isr}(t)$ and $PC_{isr}^*(t)$ are the actual and scenario-dependent production of the regulated halocarbons for end-use category s in region r at time t (kt/year), respectively, and $RC_{isr}^{\rightarrow}(t)$ is the recycled amount of CFCs ((pr.3) recycling in Figure 10.4) for end-use category s in region r at time t (kt/year), as described in Equation (10.8) in Table 10.4.

The future production of the alternatives ($PC_{isr}(t)$, $i=8,...,11$, $t > 1991$) consists of two parts; additional production due to the substitution within the CFC market ($LC_{isr}(t)$ in kt/year) and present production ($PC_{isr}(1991)$ in kt/year (s.1) in Figure 10.4) (for the imaginary substitutes this term is equal to zero). The first part is dependent on the replacement fractions ($sb_{isr}^*(t)$ in %/yr) at which by these alternatives arrive in the CFC market. Both parts are assumed to be subject to the same continuous growth, as represented by growth parameter $gr_{isr}^*(t)$ (%/yr):

$$PC_{isr}(t) = [LC_{isr}(t) + PC_{isr}(1991)]$$

$$[1 + gr_{isr}^*(t)/100] \quad (10.3)$$

$$i=8,...,11 \quad \forall s \quad \forall r$$

where:

$$LC_{isr}(t) = \int_{1991}^t \sum_{i=1}^5 \max[PC_{isr}(\tau-1) - PC_{isr}(\tau), 0.0] sb_{isr}^*(\tau) d\tau$$

Emissions: emission of halocarbons to the atmosphere already starts within the CFC industry. Some of the manufactured CFC-11 and CFC-12 is lost immediately during the production process, with no delay between production and release. These fugitive emissions (pr.4) are estimated to be equivalent to 2% of CFC-11 production and 3.3 % of CFC-12 production (CMA, 1983). Because CFC-11 and CFC-12 are now relatively more often being produced in the developing world, using older technologies, the model estimates the fractions over the last decade to be higher, namely: 2.5% for CFC-11 and 5% for CFC-12. For the other CFCs, a loss fraction of 2% is assumed in the model.

The CFC-consumption

The CFC-consumption subsystem is described by the state variable halocarbon consumption ($CC_{isr}(t)$), which depends on the required time for transporting, c.q. transferring the products of all end-use categories from the CFC-industry to the users (consumption). The state variable halocarbon consumption ($CC_{isr}(t)$) for halocarbon i ($\forall i$) for end-use category s in region r at time t is equal to $PC_{isr}(t-dic_s)$, where dic_s is the delay time between production and start of consumption (< 1 year $\forall s$).

Emissions: halocarbons emission from CFC-consumption consist of the direct halocarbon releases through the use of aerosols and open cell foams, solvents and fire extinguishers.

Landfill site (delayed-release box)

In the model, the landfill sites (delayed-release box) subsystem represents the storage of products belonging to the end-use categories: closed cell foams, hermetically and non-hermetically sealed refrigerators (already

Table 10.4: Main processes described in the system diagram of the halocarbon model ((pr.1)..(pr.12) are given in Figure 10.4).

(pr.2) usage (kt/yr):

$$CR_{isr}^{\rightarrow}(t) = CC_{isr}(t-dcd_s) \quad s=4,...,6 \quad \forall i \quad \forall r \quad (10.4)$$

where dcd_s is the delay time between start of consumption and first year at refuse dump (years) (< 1 year for $s=1,...,4$, 8 years for $s=5$, and 4 years for $s=6$).

(pr.3) recycling (kt/yr):

$$RC_{isr}^{\rightarrow}(t) = CR_{isr}^{\rightarrow}(t)r_{isr}^*(t)/100 \quad s=5,6 \quad \forall i \quad \forall r \quad (10.5)$$

where $r_{isr}^*(t)$ is the recycling fraction at region r for end-use category s at time t (%/yr).

(pr.6) directly-leaked emissions (kt/yr):

$$\begin{aligned} DiL_{is}^{\rightarrow}(t) &= \sum_{r=1}^9 dll_s [CR_{isr}^{\rightarrow}(t) - RC_{isr}^{\rightarrow}(t)] \quad i=1,2,4,5,9,...,12 \quad s=4,...,6 \\ &= 0.0 \quad \text{otherwise} \end{aligned} \quad (10.6)$$

where dll_s is the fraction of the CFC production in end-use category s released to the atmosphere, which is equal to 0.25, 0.07, 0.10 for the closed cell foams ($s=4$), and hermetically and non-hermetically sealed refrigerators ($s=5,6$), respectively.

(pr.7) delayed leaked emissions (kt/yr):

$$\begin{aligned} DeL_{is}^{\rightarrow}(t) &= \sum_{r=1}^9 dra_i HS_{isr}(t) \quad i=1,2,4,5,9,...,12 \quad s=4,...,6 \\ &= 0.0 \quad \text{otherwise} \end{aligned} \quad (10.7)$$

where dra_i is the annual fraction that leaks from the refuse dump or delayed-release box into the atmosphere. This parameter is calibrated on the basis of historical data, and is averaged over the three end-use categories equal to 0.08, 0.25, 0.10, 0.10 for CFC-11, CFC-12, CFC-114, CFC-115, resp., and 0.09 for the alternatives.

(pr.8) total emissions (kt/yr):

$$EM_i^{\rightarrow}(t) = FG_i^{\rightarrow}(t) + DE_i^{\rightarrow}(t) + \sum_{s=4}^6 [DiL_{is}^{\rightarrow}(t) + DeL_{is}^{\rightarrow}(t)] \quad \forall i \quad (10.8)$$

where $FG_i^{\rightarrow}(t)$ is the fugitive emissions during the production-process, and $DE_i^{\rightarrow}(t)$ is the total direct emissions through the use of aerosols and open cell foams ($s=1$), solvents ($s=2$) and fire-extinguishers ($s=3$).

(pr.10) direct radiative forcing (Wm^{-2}):

$$\Delta Q_{hal,dir}^{\rightarrow}(t) = \sum_{i=1}^{13} rf_i(t) C_i(t)/1000 \quad (10.9)$$

where rf_i represents the direct radiative forcing coefficients (Table 10.1, Shine *et al.*, 1990).

(pr.11) indirect radiative forcing (Wm^{-2}):

$$\Delta Q_{hal,ind}^{\rightarrow}(t) = a [Cl_x(t) - Cl_x(1970s)] \quad (10.10)$$

where a is equal to $0.0762 Wm^{-2}pptv^{-1}$, based on: $\Delta Q_{hal,ind}^{\rightarrow}$ is 80% of $\Delta Q_{hal,dir}^{\rightarrow}$ for the period 1979-1990 (Ramaswamy *et al.*, 1992), and Cl_x is the global stratospheric chlorine concentration.

(pr.12) total halocarbon radiative forcing (Wm^{-2}):

$$\Delta Q_{hal}^{\rightarrow}(t) = \Delta Q_{hal,dir}^{\rightarrow}(t) + \Delta Q_{hal,ind}^{\rightarrow}(t) \quad (10.11)$$

releasing their stored halocarbons) after usage. The time delay between initial use and the first year of releases is modelled by Equation (10.4) ((pr.2) usage). This averaged time delay is assumed to be less than one year for closed cell foams and four to eight years for refrigerators.

However, the releases of stored halocarbons in the case of refrigerators can be avoided by recycling practices (pr.3). The total amount of recycled halocarbons is modelled by a recycling fraction (r_{isr}^*) (see Equation (10.5)), which reduces the direct releases in the first year ((pr.6) to directly leaked emissions, Equation (10.6)).

These directly leaked emissions are dependent on the release fractions obtaining for each end-use category. These fractions (dll_s , $s=4,...,6$) are empirically based on the lifetime of the different products, which are: 1/4 for closed cell foams, 1/15 for hermetically sealed refrigerators, and 1/10 for non-hermetically sealed refrigerators.

The remaining quantity of stored halocarbons is now added to the total amount of halocarbons accumulated at the land fill sites (the state variable $HS_{isr}(t)$ for halocarbon i for end-use category s in region r at time t (in kt/yr)). This variable also depends on the amount of halocarbons leaking out of that land fill sites, the so-called delayed leaked emissions (pr.7). The latter process is modelled by Equation (10.7) (Wigley, 1988), in which the parameter dra_i expresses the annual fraction that leaks from the landfill sites or delayed release box into the atmosphere. This parameter is calibrated by reference to historical data, and is equal to 0.08, 0.25, 0.10, 0.10, and 0.09 for CFC-11, CFC-12, CFC-114, CFC-115, and the alternatives, respectively.

The state variable representing halocarbon storage ($HS_{isr}(t)$) represents now calculated as follows (Wigley, 1988):

$$HS_{isr}(t) = HS_{isr}(t-1) + \int_{t-1}^t [(1-dll_s) [CR_{isr}^{\rightarrow}(\tau) - RC_{isr}^{\rightarrow}(\tau)] - dra_i HS_{isr}(\tau)] d\tau \quad (10.12)$$

$$i=1,2,4,5,9,...,12 \quad s=4,...,6 \quad \forall r$$

Emissions: the emissions from the landfill sites associated with end-use categories, closed cell foams and refrigerators contribute to the direct leaked emissions (pr.6) and to delayed leaked emissions (pr.7).

Atmosphere

The atmosphere subsystem in turn consists of two subsystems: troposphere and stratosphere. The troposphere is the lower part of the atmosphere (till 8-17 km), and the stratosphere is the upper part.

Troposphere

The state of the troposphere is described by three state variables, namely: the concentration of the halocarbons, chlorine and bromine.

The state variable tropospheric concentration of the halocarbons ($C_i(t)$ in pptv) is determined by the initial concentration, the emissions and the atmospheric removal by photodissociation. The removal rate of halogenated halocarbons (CFCs, CCl_4 ; $i=1,...,6$; halons: $i=12,13$) is modelled as being inversely proportional to the atmospheric lifetimes of halocarbons. These halocarbons are assumed to be removed from the atmosphere due to stratospheric losses strictly in proportion to their concentrations. The fraction of halocarbons remaining at time t is then expressed by the negative exponential function $\exp(-t/L_i)$, where L_i is the atmospheric lifetime of the halocarbon (viz. Prather *et al.* (1992), Table 8.1). The concentration is then as follows:

$$C_i(t) = C_{i-1}(t-1) + \int_{t-1}^t [cf_i EM_i^{\rightarrow}(\tau) - C_i(\tau)/L_i] d\tau \quad (10.13)$$

$$i=1,...,6,12,13$$

where cf_i is the conversion factor for halocarbon i (pptv/kt).

The currently used halocarbons (CH_3CCl_3 and HCFC-22: $i=7,8$ and the three alternatives: $i=9,10,11$) are destroyed in the troposphere by reaction with OH (stratospheric destruction is of minor importance). The tropospheric concentrations of these gases are

now described as:

$$C_i(t) = C_{i-1}(t-1) + \int_{t-1}^t [cf_i EM_i^{-1}(\tau) - C_i(\tau)(1/sL_i - k_i C_{OH}(\tau))] d\tau \quad (10.14)$$

$i=7, \dots, 11$

where sL_i is the stratospheric lifetime (Prather *et al.*, 1992; and Table 10.3); k_i the coefficient of the rate of reaction of halocarbon i with OH, which is equal to $(C_{OH}(1990).tL_i)^{-1}$ (ppmv⁻¹years⁻¹); and where $C_{OH}(t)$ is the average tropospheric OH concentration at time t (ppmv), and tL_i the tropospheric lifetime (Prather *et al.*, 1992; and Table 10.3). The OH concentration is calculated in the IMAGE methane module (experimental version 1.6), as described in Rotmans *et al.* (1992).

The state variable for the tropospheric chlorine concentration ($Cl(t)$ in ppbv) is modelled as follows:

$$Cl(t) = Cl_{ic} + \sum_{i=1}^{11} n(i)C_i(t)/1000 \quad (10.15)$$

where $n(i)$ is the number of chlorine atoms per molecule of compound i , and Cl_{ic} the initial tropospheric chlorine concentration, which is 0.6 ppbv (from CH₃Cl).

The tropospheric bromine concentration is modelled in a manner which is similar to that employed for the tropospheric chlorine concentration. Here the initial concentration is equal to 15 pptv (from CH₃Br).

Stratosphere

Tropospheric chlorine loading will manifest itself as lower stratospheric chlorine (Cl_x) after a time delay of 2-4 years (whereby, in this study 4 years is assumed, viz. Prather *et al.* (1992)), and allowance is made for systematic discrepancies in absolute quantities due to incomplete oxidation of the halocarbon source gases. These discrepancies are dependent on the fraction of each halocarbon molecule which is photochemically destroyed in the lower stratosphere and thus contributes to the quantity of chlorine in the lower stratosphere. For example, CH₃CCl₃ molecules are readily photolyzed in the lower stratosphere, and thus release almost all of their Cl atoms to Cl_x . However, HCFC-22 remains partially intact and

releases only a fraction of its chlorine loading as Cl_x . The state variable for lower stratospheric chlorine abundance, which is a measure of the chlorine present in the stratosphere which can contribute to ozone depletion, is calculated as the weighted sum of the chlorine loadings of the source gases (ppbv):

$$Cl_x(t) = Cl_{x,ic} + \sum_{i=1}^{11} w_i C_i(t-dts)/1000 \quad t \geq 1904$$

$$= Cl_{x,ic} \quad t < 1904 \quad (10.16)$$

where w_i is the stratospheric chlorine weight factor of halocarbon i (Table 10.1, Prather *et al.*, 1988); dts is the delay time for transport between the troposphere and the stratosphere (= 4 years); and $Cl_{x,ic}$ is the initial concentration of lower stratospheric chlorine which obtained in the year 1900 (assumed to be equal to ~0.6 ppbv). The lower stratospheric bromine concentration (Br_x) is modelled in a manner similar to that in which the lower stratospheric chlorine concentration is modelled.

The Earth's surface

The only state variable relevant to the system Earth's surface is the equilibrium temperature, which is induced by radiative perturbation (forcing) associated with the greenhouse gases, including the halocarbons. The equilibrium temperature increase ($\Delta T_{eq}(t)$ in °C) is modelled in IMAGE (experimental version 1.6) as:

$$\Delta T_{eq}(t) = \Delta Q_{tot}^{-}(t)/\lambda \quad (10.17)$$

where $\Delta Q_{tot}^{-}(t)$ is the total radiative forcing due to changes in the concentration greenhouse gases (Wm⁻²), including the total halocarbon forcing $\Delta Q_{hal}^{-}(t)$ (pr.12). The latter consists of two parts: the direct radiative forcing associated with halocarbons (pr.10, Equation (10.9)) and the indirect radiative forcing due to stratospheric ozone losses (pr.11, Equation (10.10)). The latter process is a potentially important feedback which has a bearing on the overall radiative forcing due to halocarbons, and has been dubbed stratospheric-ozone-depletion feedback (Wigley and Raper, 1992). Indirect ozone forcing is modelled according to Equation (10.10), fol-

lowing Wigley and Raper (1992). The parameter a in Equation (10.10) is estimated on the result published by Ramaswamy *et al.* (1992), namely that over the period between 1979 and 1990 globally averaged negative forcing due to ozone depletion has set off 80% of the direct total CFC forcing. It could be argued that this modelling technique is too far removed from the real world, but for the purposes of this study, it nevertheless yields useful insights into the role of this feedback mechanism. Therefore, in the calculations besides the direct radiative forcing, also the overall radiative forcing (including the radiative effects of the stratospheric-ozone-depletion feedback) due to halocarbons will be presented. Consequently, the halocarbon model is run in two modes, namely: the base case (without the stratospheric ozone depletion feedback) and the feedback case.

10.6 Results

10.6.1 Introduction

Figure 10.5 shows that the simulated CFC-12 concentrations over the period 1970 to 1990 match the observed values (1970-1990) (Fraser *et al.*, 1992; WMO, 1990a). For the other halocarbons included in the model, the differences between the observed and simu-

lated concentrations are of the same order, always less than 2-3%. In Figure 10.6a, the simulated atmospheric chlorine loading over the period 1900 till 1990 is given. The atmospheric chlorine level in the year 1990 was about 3.6 ppbv, which is comparable with the sum of the chlorine loadings of the observed atmospheric concentrations of the halocarbons which are included in the model, namely: 3.5 ppbv (Fraser *et al.*, 1992). The discrepancy of about 0.32 ppbv from the central estimate of 3.9 ppbv of the atmospheric chlorine loading quoted by Fraser *et al.* (1992) can be explained if the chlorine loadings of the halocarbons excluded from the model are considered.

Simulated atmospheric bromine loading (which comprises CH_3Br , halon-1211 and halon-1301) is 20 pptv, which corresponds with the observed bromine loading of these compounds, namely: 20 pptv. Other natural sources of bromine, over and above CH_3Br , account for the 20 pptv difference from the observed atmospheric bromine level of 40 pptv.

In Figure 10.6b, the simulated direct and overall radiative forcing associated with the halocarbons over the period 1900-1990 is given. Direct radiative forcing is about 0.25 Wm^{-2} over the period 1900-1990, while if stratospheric-ozone-depletion feedback is included, overall radiative forcing is reduced to 0.14 Wm^{-2} .

As an illustration of the delayed mecha-

Figure 10.5: Simulated and observed CFC-12 concentration over the period 1900 to 1990. The observed concentrations over the period 1970 to 1989 are based on Fraser *et al.* (1992).

Figure 10.6a: Relative contribution of the halocarbons to the atmospheric chlorine concentration over the period 1900 to 1989.

nisms in the model, *Figure 10.7* depicts the response of the emissions and concentration of CFC-12 to an immediate 1992-phase out of the production of CFC-12. The delay time between production and emission is about 5-10 years. CFC-12 concentration follows an increasing trend until 2000, after which it slowly decreases as a result of the phasing-out process.

10.6.2 Halocarbon scenarios

This section addresses a number of policy

questions regarding possible options aimed at strengthening the London Amendments (e.g. option 6 of the Copenhagen Amendments of 1992), or conversely, options involving delayed phase-outs and/or continuing future halocarbon production in non-complying countries (e.g. the IPCC-1990 scenarios). In all cases, the model-calculations relevant to the various halocarbon production scenarios under consideration are presented with respect to: (1) future atmospheric chlorine levels (associated with ozone losses at the middle and high latitudes

Figure 10.6b: Direct halocarbon radiative forcing and overall halocarbon forcing (including the stratospheric ozone depletion feedback) over the period 1900 to 1990.

Figure 10.7: Response of the emissions and concentration of CFC-12 to an immediate 1992-phase-out of the production of CFC-12.

and above the Antarctic), and (2) radiative forcing associated with the halocarbons. The results will be compared with those which would result from a best implementation of the London Amendments (reference case). For equivalent model-conditions, and for all cases (except option 0), an identical future hydroxyl radical (OH) trend is assumed (the simulated OH trend according to the IPCC-1990 Control Policies scenario). In option 7, future atmospheric bromine levels associated with various strategies for the brominated halocarbons included in the model are studied. Besides being evaluated in terms of the various scenarios, each case are evaluated from the risk perspective, and the scenarios are thus tested against the four ozone targets as defined by Prather *et al.* (1992) which are described below. Because halocarbons only marginally contribute to global warming, no climate targets have been developed for them. In this analysis, direct halocarbon forcing and overall halocarbon forcing are compared with the reference value of 0.2 Wm^{-2} (the direct radiative halocarbon forcing level which obtained during the middle of the last decade) (see Figure 10.6b). This level is about six to seven times the simulated overall radiative halocarbon forcing.

Ozone targets - The first target (*peak chlorine*) is to minimize the peak chlorine loading of the atmosphere, since this is expected to coincide with the largest ozone

depletion in the middle and high latitudes and above the Antarctic. The second target (*year at 3 ppbv level*) is to reduce the atmospheric chlorine as soon as possible to the level of 3 ppbv (the chlorine abundance which obtained around 1985, the middle of the decade which the first signs of ozone depletion were observed at middle latitudes in spring and summer) (see Figure 10.6a). The third target (*year at 2 ppbv level*) is similar to the second target in that the aim is to return as soon as possible to a chlorine level of 2 ppbv (the chlorine abundance in the late 1970s when the Antarctic ozone hole as well as the accelerated trends in the total ozone column in the Northern Hemisphere were first observed) (Prather and Watson, 1990). The 2 ppbv-level is internationally seen as the no-effect level, and as a possible sustainable target. The fourth target (*Integral (Cl above 3 ppbv)*) is to minimize the accumulated chlorine abundance above the level of 3 ppbv, which is a measure of stratospheric ozone depletion over recent and coming years. According to the WMO (1992), each 0.1 ppbv of chlorine above 3 ppbv would lead to an additional stratospheric ozone decrease of about 0.75% in winter and 0.5% in summer at middle latitudes.

Reference case

The reference case is based on the best esti-

Figure 10.8: Relative contribution by halocarbons to the atmospheric chlorine concentration for the reference case.

HCFC-22 / other alternatives
 CH₂Cl₂
 CCl₄
 CFC-113 / CFC-114 / CFC-115
 CFC-12
 CFC-11
 CH₃Cl

mate of future chlorine/bromine emissions, assuming full compliance with the London Amendments. It also assumes a compliance to the phasing-out of HCFC-22 by 2040, but no restrictions before 2020 (WMO, 1992):

- (i) CFCs : 50% reduction in 1995; 85% in 1997; and 100% in 2000.
- (ii) CCl₄ : 85% reduction in 1995; and 100% in 2000.
- (iii) CH₂Cl₂ : 30% reduction in 1995; 70% in 2000; and 100% in 2005.
- (iv) Halons : 50% reduction in 1995; and 100% in 2000.
- (v) Alternatives : HCFC-X, 30% substitution; HCFC-Y 10% substitution; and HFC-Z 10% substitution, starting in 1997, with a growth of 3%/annum until 2040, subsequently to be reduced to zero by 2040.
- (vi) For the developing world, with an assumed consumption of 20% of the global production in 1991, a 10-year period of grace is assumed, during which production remains at the present level.

Figure 10.8 depicts the relative contributions of the various halocarbons to the atmospheric chlorine concentration for this reference case. The chlorine level of 2 ppbv is to be reached in the second half of the next century, in 2070 (see Table 10.5), at which time the long-lived CFCs, i.e. CFC-11 and CFC-12, will still be contributing about 60% to

this 2 ppbv level of atmospheric chlorine loading.

Question 0: What are the ozone and halocarbon-climate implications for the IPCC-1990 scenarios?

The four IPCC-1990 scenarios (IPCC, 1991b) assume a wide range of policies for the halocarbons. The IPCC-1990 Business-as-Usual (BaU90) scenario assumes that the Montreal Protocol is not superseded by stricter measures and that participation of the developing countries is only 85%. In the IPCC-1990 Low Emissions (Low90) scenario, there is a full compliance with the Montreal Protocol. A strengthened Montreal Protocol, as assumed for the IPCC-1990 Control Policies (CP90) and the Accelerated Policies (AP90) scenario, includes a phasing-out of CFCs and halons by 2000 (as in the London Amendments). In all scenarios, the substitute HCFC-22 only captures 35% of the reduced CFC market, and in addition, itself grows by 2.5% annually until 2050 (see also Chapter 5). Since the development of these scenarios, the production of CFCs has already been reduced by 40% compared to the 1986-level, and the Copenhagen Amendments were adopted in 1992. Therefore, the BaU90 and Low90 scenarios represent an unlikely future for CFC emissions. Firstly, the emissions of CFC-11,

Figure 10.9: CFC-11 equivalent emissions for the four IPCC-1990 scenarios and the reference case (London Amendments).

CFC-12 and HCFC-22 have been calculated for the four IPCC-1990 scenarios using the halocarbon model. Since the original IPCC-1990 scenarios only consider these three halocarbons, the same scenario assumptions for CFC-11 and CFC-12 were here used for the other CFCs. For methylchloroform and carbon tetrachloride, the emissions are assumed to remain constant at their 1991 levels in the BaU90 and Low90 scenarios. In the CP90 and AP90 scenarios, CCl_4 and CH_3CCl_3 -emissions are assumed to follow the reduction trajectories as defined in the London Amendments.

Ozone - Using the concept of ODPs, the emissions of non-CFC-11 gases can be combined with emissions of CFC-11 and expressed as CFC-11-equivalent emissions (Figure 10.9). Here, the revised ODP values adopted by Pyle *et al.* (1992) (Table 10.2) are used. In all IPCC-1990 scenarios, the CFC-11 equivalent emissions first decline as a result of the present reductions and the control measures enshrined in the Montreal Protocol and the London Amendments, and subsequently slowly increase again, primarily because of the increase in HCFC-22 emissions.

Figure 10.10a: Atmospheric chlorine concentration for the four IPCC-1990 scenarios and the reference case.

(dark shaded area indicates maximum ozone risks where 3 ppbv target of atmospheric chlorine loading is exceeded, light shaded area indicates high ozone risks where 2 ppbv target of chlorine loading is exceeded).

— IPCC-1990 Business-as-Usual scenario
 - - - IPCC-1990 Low emission scenario
 . . . IPCC-1990 Control Policies scenario and Accelerated Policies scenario
 - . - . - reference case (London Amendments)

Figure 10.10a shows the resulting chlorine concentration for the IPCC-1990 scenarios and the reference case. In this Figure, three ozone risk areas are identified which indicate the potential ozone risk with respect to atmospheric chlorine loading: a maximum ozone risk area (>3 ppbv), a high ozone risk area (>2 and <3 ppbv), and low/moderate ozone risk area (<2 ppbv). In all IPCC-1990 scenarios chlorine loading exceeds the 3 ppbv level, and thus all IPCC-1990 scenarios are maximum ozone risk scenarios. Only the reference case tends to indicate low/moderate ozone risks in the second half of the next century. However, even this reference case is associated with maximum ozone risks for the coming decades, up to about 2040. Table 10.5 summarizes the resulting ozone targets for the four IPCC-1990 scenarios and for the reference case.

Climate - Direct halocarbon forcing and overall halocarbon forcing (including the stratospheric-ozone-depletion feedback) are given in Figure 10.10b. For this Figure, two halocarbon-climate risk areas are tentatively identified which indicate the potential climate risks due to the halocarbons: a low halocarbon-climate risk area (in which halocarbon forcing (direct or overall forcing) is less than 0.2 Wm^{-2}), and a moderate halocarbon-climate risk area (in which halocarbon forcing exceeds 0.2 Wm^{-2}). Here, the risks associated with exceeding the two absolute

ozone targets (namely: 2 ppbv and 3 ppbv-level) are estimated as being higher than the halocarbon-climate risks associated with exceeding the 0.2 Wm^{-2} -level.

The most significant effect of the stratospheric-ozone-depletion feedback is found in the BaU90 scenario, and results from the increasing atmospheric chlorine concentration envisaged in this scenario. According to the BaU90 scenario, direct halocarbon radiative forcing is about 1.2 Wm^{-2} over the period 1990-2100, and this is reduced to 0.4 Wm^{-2} due to the feedback. For the other IPCC-1990 scenarios, the effect of the stratospheric-ozone-depletion feedback is a reduction in halocarbon forcing, although not sufficient to achieve the radiative target level of 0.2 Wm^{-2} . In the reference case, the effect of this feedback is precisely the opposite, since the overall halocarbon forcing over the period 1990-2100 would be slightly increasing, while direct halocarbon forcing over the same period only declines gradually (and after 2055 leaves the moderate halocarbon-climate risk area) (see also Table 10.5). This is a direct result of the fact that due to the strong reductions in halocarbon emissions for the reference case, the atmospheric chlorine levels falls below the present levels after 2030, and therefore decrease, the magnitude of (negative) ozone forcing, thus increasing overall halocarbon forcing.

This feedback result leads to the interest-

Figure 10.10b: Direct halocarbon radiative forcing and overall halocarbon forcing (including the stratospheric ozone depletion feedback) for the four IPCC-1990 scenarios and the reference case.

(dark shaded area indicates where 0.2 Wm^{-2} target of direct halocarbon forcing is exceeded and light shaded area indicates where 0.2 Wm^{-2} target of overall halocarbon forcing is exceeded).

- ① direct radiative forcing
- ② overall radiative forcing
- IPCC-1990 Business-as-Usual scenario
- ==== IPCC-1990 Low emission scenario
- IPCC-1990 Control Policies scenario and Accelerated Policies scenario
- .-.-.- reference case (London Amendments)

Table 10.5: Scenarios for future chlorine and halocarbon forcing levels

Option	peak (ppbv)	Date of achieving 3 ppbv	Date of achieving 2 ppbv	Integral chlorine (Cl above 3 ppbv)	Period above 0.2 Wm ⁻² n ^a	Period above 0.2 Wm ⁻² fb ^b
Reference case	3.95	2040	2070	30.0	1985-2055	2015-2050
0. IPCC-1990 scenarios						
Business-as-Usual scenario	11.9	-	-	543	1985-2100	2010-2100
Low Emissions scenario	10.0	-	-	463	1985-2100	2010-2100
Control Policies scenario	5.9	-	-	205	1985-2100	2010-2100
Accelerated Policies scenario	5.2	-	-	188	1985-2100	2010-2100
1. Participation in Protocol						
participation 90%	3.95	2045	-	35	1985-2070	2015-2045
participation 80%	3.95	2060	-	43	1985-2100	2015-2045
participation 50%	4.5	-	-	138	1985-2100	2015-2050
2. Role of developing world						
no grace period	3.9	2035	2065	26	1985-2055	2015-2050
phase-out in 2040	4.0	2055	2095	53	1985-2075	2015-2050
no control	5.7	-	-	194	1985-2100	1985-2100
3. Timing phase-out CFCs						
phase-out 1995	3.8	2030	2065	19	1985-2055	2015-2050
phase-out 1997	3.8	2035	2065	23	1985-2055	2015-2050
phase-out 2005	4.1	2045	2080	42	1985-2065	2015-2050
phase-out 2010	4.35	2050	2090	56	1985-2070	2015-2045
4. Influence of HCFC-22						
complete phase-out 1995	3.8	2020	2060	14	1985-2045	-
complete phase-out 2000	3.9	2030	2070	21	1985-2050	2015-2050
no control HCFC-22	4.0	2070	-	37	1985-2100	2015-2100
no control HCFC-22/other alt.	4.0	-	-	54	1985-2100	2015-2100
5. Role of alternatives						
sub. X,30%;Y,10%;Z,10%	3.95	2045	-	32	1985-2100	2015-2100
sub. X,50%	3.95	2050	-	34	1985-2100	2015-2100
sub. Y,50%	3.95	2040	2085	30	1985-2065	2015-2055
sub. Z,50%	3.95	2035	2070	28	1985-2100	2015-2100
6. Accelerated complete phase-out						
Copenhagen Amendments	3.8	2020	2060	17	1985-2040	-
maximum effort	3.75	2010	2050	11	1985-2030	-
7. Timing phase-out halons ^c						
participation 100% (reference)	4.6	2045	-	55	1985-2055	2015-2050
participation 90%	4.6	2050	-	60	1985-2055	2015-2050
participation 80%	4.6	2055	-	65	1985-2055	2015-2050
participation 50%	4.8	-	-	92	1985-2055	2015-2050

^a Without the stratospheric-ozone-depletion feedback.^b With the stratospheric-ozone-depletion feedback.^c In stratospheric chlorine-equivalent concentration (with an assumed delay time for the transport to the lower stratosphere of 4 years, the 1990 values in the model are: Cl_x-value, 2.96 ppbv; Br_x-value, 18.5 pptv; and Cl_{x,eq}-value (the Cl_x-value plus 40 times the Br_x-value), is 3.7 ppbv. Following Prather *et al.* (1992) it is here assumed that bromine atoms are 40 times more effective than chlorine atoms in depleting stratospheric ozone.

ing conclusion that severe reductions in halocarbon emissions as regulated by the London Amendments will lead to an increase in overall radiative forcing due to halocarbons over the period 1990-2100, and thus have negative implications for the climate change problem. Nevertheless, the effect in terms of radiative forcing is relatively small, an increase of less than 0.2 Wm^{-2} over the period 1990-2100.

Question 1: What are the implications of a limited level of participation in the London Amendments?

In this policy option, the impact of a partial phase-out of all regulated halocarbons (CFCs, CCl_4 and CH_2Cl_2) is examined. Participation levels considered are: 100% (all regions complying, reference case), 90% (only 50% of the developing world not complying, participation 90%), 80% (developing world not complying, participation 80%), and 50% (EC and OECD only partially complying, participation 50%), the percentages here referring to the London Amendments. In all cases the production in the non-complying regions is assumed to stabilize at its present consumption level.

Ozone - Figure 10.11a depicts the atmospheric chlorine concentrations associated with these four cases. The small increases in chlorine levels around 2030 which the Figure

indicates for all cases coincides with the peak value in the HCFC-22 concentration at that time. This option shows that if the participation under the terms of the London Amendments is less than, or equal to, 90%, chlorine loading will never return to the 2 ppbv level, and the entire next century will therefore be associated with high/maximum ozone risks. In the most pessimistic case of a mere 50% participation, chlorine abundance stabilizes at present levels, which inevitably implies maximum ozone risks over the entire 21st century. The values of the other ozone targets are shown in Table 10.5.

Climate - Direct halocarbon forcing and overall halocarbon forcing (including the stratospheric-ozone-depletion feedback) is depicted in Figure 10.11b. Insofar as direct halocarbon forcing is concerned, the differences between the four cases are significant. Participation of at least 80% is necessary if there is to be a return to the 0.2 Wm^{-2} level.

Allowing for the feedback once again leads to increases in overall halocarbon forcing over the period 1990-2100. In all cases the overall forcing leaves in the low halocarbon-climate risk area for only 30-35 years.

Question 2: What are the consequences of the various policies for the developing world?

In this policy option, the role of the develop-

Figure 10.11a: Atmospheric chlorine concentration for different levels of participation to the London Amendments (option 1).

(dark shaded area indicates maximum ozone risks where 3 ppbv target of atmospheric chlorine loading is exceeded. light shaded area indicates high ozone risks where 2 ppbv target of chlorine loading is exceeded).

— participation 50%
 - - - participation 80%
 . . . participation 90%
 - . - . participation 100% (reference case)

Figure 10.11b: Direct halocarbon radiative forcing and overall halocarbon forcing (including the stratospheric ozone depletion feedback) for different levels of participation of the London Amendments (option 1).

(dark shaded area indicates where 0.2 Wm^{-2} target of direct halocarbon forcing is exceeded and light shaded area indicates where 0.2 Wm^{-2} target of overall halocarbon forcing is exceeded).

- ① direct radiative forcing
- ② overall radiative forcing
- participation 50%
- - - participation 80%
- . . . participation 90%
- · - · participation 100% (reference case)

ping world (20% of CFC-consumption in 1991) is studied in more detail. The reference case assumes a 10-year grace period for the developing countries. The first case (no grace period) describes the CFC policy of the developing world assuming that their reduction scheme is the same as for the developed world, i.e. there is no grace period. In the second case (phase-out in 2040) the consumption of the regulated halocarbons (CFCs, CCl_4 , and CH_3CCl_3) in the developing world grows by 2.5% annually up to 2020 and is then phased out by 2040. Finally, in the case the absence of control (no control), the consumption of regulated halocarbons rises until 2040 (2.5% annually), at which level it stabilizes.

Ozone - The case in which there is no grace period exhibits marginal differences vis-à-vis the reference case; 1-2% reduction of the peak of chlorine loading, and the chlorine level reaches the 2 ppbv- and 3 ppbv level five years before the dates in the reference case (Figure 10.12a and Table 10.5). The accumulated chlorine abundance above 3 ppbv is now reduced by about 15%. These results indicate that abolishing the grace period for the developing world would only yield marginal benefits in terms of ozone risks. The latter two cases, in which the developing world delays its phase-out measures or merely stabilizes its emissions, involve considerable impacts on the chlorine levels.

A delayed phase-out (phase-out in 2040) places the achievement of 2 ppbv further into the future, and thus the period associated with high ozone risks is extended about 25 years, enduring till the end of the next century. The same delay-time applies to the date of the achievement of the peak chlorine. In the case of no-control, the chlorine concentration continuously increases up to a peak value of 5.7 ppbv by 2100, and none of the ozone targets are achieved (maximum ozone risk scenario).

Climate - As regards direct halocarbon forcing, similar results are found (Figure 10.12b). Delay (phase-out in 2040) adds about 25 years to the period required for achieving the 0.2 Wm^{-2} level. However, since overall radiative halocarbon forcing (including the stratospheric-ozone-depletion feedback) exceeds this level only marginally for a short time-period of 30-40 years, all cases (except the case of no control) are low halocarbon-climate risk scenarios.

Question 3: What is the effect of the timing of phasing-out the currently regulated halocarbons (CFCs, CCl_4 and CH_3CCl_3)?

In order to answer this question, it is assumed that the production of the regulated halocarbons (CFCs, CCl_4 and CH_3CCl_3) will be eliminated in different years, the years in

Figure 10.12a: Atmospheric chlorine concentration for different policies for the developing world (option 2).

(dark shaded area indicates maximum ozone risks where 3 ppbv target of atmospheric chlorine loading is exceeded, light shaded area indicates high ozone risks where 2 ppbv target of chlorine loading is exceeded)

— no control
- - - phase-out in 2040
- . - . - reference case
. no grace period

question being: 1995 (phase-out 1995), 1997 (phase-out 1997), 2000 (reference case, phase-out 2000), 2005 (phase-out 2005) and 2010 (phase-out 2010), respectively. The assumed reduction scheme for the 1995 phase-out is as follows: 75% reduction by 1993 (CFCs); 85% by 1994 (CCl_4); and 50% by 1993 (CH_3CCl_3) (1 year before the date envisaged in the reduction scheme of the Copenhagen Amendments), and then for all these compounds a phasing-out by 1995. For the developing world, a 10-year grace period is still being assumed. All cases are technically feasible, although the accelerated

phase-outs (phase-out 1995 and phase-out 1997) will involve increased costs associated with replacing existing equipment (UNEP, 1991a).

Ozone - Figure 10.13a depicts the atmospheric chlorine loadings associated with the five cases. This Figure shows that neither a 1995 phase-out nor a 1997 phase-out makes more than marginal differences. A 1995 or 1997 phase-out for the industrialized world could decrease the peak chlorine loading by almost 5%, and reduce the period associated with maximum ozone risks by about ten years less than the period envisaged.

Figure 10.12b: Direct halocarbon radiative forcing and overall halocarbon forcing (including the stratospheric ozone depletion feedback) for different policies for the developing world (option 2).

(dark shaded area indicates where 0.2 Wm^{-2} target of direct halocarbon forcing is exceeded and light shaded area indicates where 0.2 Wm^{-2} target of overall halocarbon forcing is exceeded).

① direct radiative forcing
② overall radiative forcing
— no control
- - - phase-out in 2040
- . - . - reference case
. no grace period

Figure 10.13a: Atmospheric chlorine concentration of different timing of CFCs/ CCl_4 / CH_3CCl_3 phase-out (option 3).

(dark shaded area indicates maximum ozone risks where 3 ppbv target of atmospheric chlorine loading is exceeded, light shaded area indicates high ozone risks where 2 ppbv target of chlorine loading is exceeded).

— phase-out 2010
 - - - phase-out 2005
 - . - . - phase-out 2000 (reference case)
 phase-out 1997
 - - - - - phase-out 1995

ged in the London Amendments (reference case). In both the 1995 and 1997 cases, the accumulated chlorine abundance above 3 ppbv is reduced by about 35% and 25%, respectively.

In general, each five-year time delay in the phase-out schedule increases peak chlorine loading by about 0.2 ppbv (about 5%), until a final range is reached which varies from about 3.8 to about 4.4 ppbv depending on whether the phase-out occurs in 1995 or 2010. Furthermore, the date by which chlorine abundance falls to 2 ppbv is also delayed, resulting in a time-difference of 25 years between the 1995 phase-out (accomplished by 2065) and the 2010 phase-out (accomplished by 2090).

Climate - Direct radiative forcing associated with the halocarbons follows a similar trend to that associated with chlorine loading (Figure 10.13b). If the whole world needs a grace period of 10 years before outlawing the regulated halocarbons, then compared to the time schedule envisaged in the London Amendments, the delay in reaching the 0.2 Wm^{-2} level will be 15 years. In all cases, direct halocarbon forcing falls to the 0.2 Wm^{-2} level before the ozone target of 2 ppbv is achieved. All cases corresponds with low halocarbon-climate risks after 2050. The overall halocarbon forcing (including the stratospheric-ozone-depletion feedback) hardly differs among the four cases (Figure 10.13b).

Question 4: What are the effects of an accelerated phase-out as opposed to a continued rise in consumption of HCFC-22?

This question relates to the previously-mentioned option of timing the phasing-out of the regulated halocarbons. In the first two cases (complete phase-out 1995 and complete phase-out 2000), the same assumptions which applied in the cases of phase-out by 1995 and phase-out by 2000 of option 3 are made, albeit with the addition of a phase-out of HCFC-22 by 2000 for both cases. The feasibility of such an earlier HCFC-22 phase-out has not yet been examined, and therefore these cases are no more than hypothetical devices enabling the effects of HCFC-22 emissions to be studied. The third and fourth case are implementations of the reference case. In the third case (no control of HCFC-22) the consumption of HCFC-22 grows at an annual rate of 2.5% until 2040 and subsequently remains at that level. Finally, in the fourth case (no control HCFC-22/other alt.) the same rate of growth in the consumption of the other alternatives (HCFC-X, HCFC-Y and HFC-Z) is assumed.

Ozone - Figure 10.14a and Table 10.5 show that a complete phase-out of all currently used halocarbons, including the consumption of HCFC-22, brings forward the dates of the realization of the 2 ppbv and

Figure 10.13b: Direct halocarbon radiative forcing and overall halocarbon forcing (including the stratospheric ozone depletion feedback) of different timing of CFC/CCl₄/CH₃CCl₃ phase-out (option 3).

(dark shaded area indicates where 0.2 Wm^{-2} target of direct halocarbon forcing is exceeded and light shaded area indicates where 0.2 Wm^{-2} target of overall halocarbon forcing is exceeded).

- ① direct radiative forcing
- ② overall radiative forcing
- phase-out 2010
- - - phase-out 2005
- · - · - phase-out 2000 (reference case)
- · · · · phase-out 1997
- - - - - phase-out 1995

3 ppbv targets, vis-à-vis a phase-out without HCFC-22 (option 3). Following a complete phase-out in 1995, the atmospheric chlorine concentration reaches the 3 ppbv level as early as 2020, about ten years in advance of the 3-ppbv date expected from the 1995 phase-out which ignores HCFC-22 (option 3). A similar time difference is found between the 3 ppbv dates of a complete phase-out in 2000 and the 2000 phase-out envisaged in option 3 (reference case). Thus a phase-out including the abolition of HCFC-22 consumption would significantly reduce the periods associated with maximum ozone

risks, a fact which is reflected in the 55% reduction of the accumulated chlorine abundance above 3 ppbv compared to the reference case which would result from a complete phase-out in 1995.

Figure 10.14a also shows that chlorine loading in the third and the fourth case follows a downward trend. In both cases, this trend can be explained by the fact that the decreasing concentrations of the long-life CFCs (ODP about 1) more than cancel out the increasing concentrations of the alternatives (ODPs less than or equal to 0.1) in their effect on chlorine abundance. Nevertheless

Figure 10.14a: Atmospheric chlorine concentration for different policies of HCFC-22 (and other alternatives) (option 4).

(dark shaded area indicates maximum ozone risks where 3 ppbv target of atmospheric chlorine loading is exceeded, light shaded area indicates high ozone risks where 2 ppbv target of chlorine loading is exceeded).

- no control HCFC-22 / other alt.
- - - no control HCFC-22
- · - · - reference case
- · · · · complete phase-out 2000
- - - - - complete phase-out 1995

these cases show that a continued growth in the production of alternatives (including HCFC-22) in the next century corresponds to maximum ozone risks. In the case of no control of HCFC-22, whatsoever, the 3 ppbv-level is reached by 2070, about 30 years later than in the reference case. However, if the production of the other alternatives is also unbridled the 3 ppbv-level is not reached in the next century (maximum ozone risk scenario).

Climate - In both phase-out cases, direct halocarbon forcing reaches 0.2 Wm^{-2} before the 2 ppbv dates, and both cases conform to low halocarbon-climate risk scenarios (Figure 10.14b). In the other two cases, direct halocarbon forcing increases, to about 0.3 Wm^{-2} (in the case of no control of HCFC-22), and to about 0.45 Wm^{-2} (in the case of no control of HCFC-22/other alt.) (Figure 10.14b). In both cases, this increase results from the fact that the increasing direct radiative effects due to the increasing concentrations of the alternatives (GWP approx. 1500-2000) more than cancel out the reduction in the decreasing direct radiative effects due to the decreasing concentrations of the long-life CFCs (GWP between 1500 and 9000, averaged value approx. 4500).

Since for all cases, atmospheric chlorine loading decreases over the period 1990-2100, overall halocarbon forcing increases even more than direct halocarbon forcing

over the same period 1990-2100. In the case of no control HCFC-22/other alt. the overall radiative forcing exceeds 0.2 Wm^{-2} , and therefore tends to represent a moderate halocarbon-climate risk.

To summarize, phasing-out HCFC-22 before 2000, combined with the phasing-out of the halocarbons which are already regulated, results in a significant shortening of the period associated with maximum ozone risks by at least a decade. However, growth in the production of HCFC-22 and other alternatives would have the opposite effect, and extend the period of maximum ozone risks up to the second half of the next century at the earliest, and also demonstrate moderate halocarbon-climate risks.

Question 5: What is the impact of the levels of substitution by HCFC-X, HCFC-Y and HFC-Z?

Discontinuing the use of CFCs implies substitution by various quantities of HCFC-X, HCFC-Y and HFC-Z. Substitution is assumed to have started in 1990, the substitution fraction being: HCFC-X, 30%; HCFC-Y, 10%; HFC-Z, 10% (first case: sub. X,30%; Y,10%;Z,10%), HCFC-X, 50%; HCFC-Y, 0%; HFC-Z, 0% (second case: sub. X,50%), HCFC-X, 0%; HCFC-Y, 50%; HFC-Z, 0% (third case: sub. Y,50%), and HCFC-X, 0%; HCFC-Y, 0%; HFC-Z, 50% (fourth case:

Figure 10.14b: Direct halocarbon radiative forcing and overall halocarbon forcing (including the stratospheric ozone depletion feedback) for different policies of HCFC-22 (and other alternatives) (option 4).

(dark shaded area indicates where 0.2 Wm^{-2} target of direct halocarbon forcing is exceeded and light shaded area indicates where 0.2 Wm^{-2} target of overall halocarbon forcing is exceeded).

- ① direct radiative forcing
- ② overall radiative forcing
- no control HCFC-22 / other alt.
- - - no control HCFC-22
- · · · · reference case
- - - - - complete phase-out 2000
- · - · - complete phase-out 1995

Figure 10.15a: Atmospheric chlorine concentration for different policies for the substitution by HCFC-X, HCFC-Y, and HFC-Z (option 5).

(dark shaded area indicates maximum ozone risks where 3 ppbv target of atmospheric chlorine loading is exceeded; light shaded area indicates high ozone risks where 2 ppbv target of chlorine loading is exceeded).

— sub X, 50%
 --- sub X, 30%, Y, 10%, Z, 10%
 - - - reference case
 - - - sub Y, 50%
 - - - sub Z, 50%

sub. Z, 50%). It is assumed that the consumption of these alternatives will grow at an annual rate of 2.5% until 2040, when it will stabilize.

Ozone - Maximum chlorine loading occurs in the same year for all cases (Figure 10.15a). The first case (sub. X, 30%; Y, 10%; Z, 10%) shows that the growth in the consumption of the alternatives extends the period required for reaching the 2 ppbv-level until the year 2100, almost 30 years later than in the reference case. In the case of 50% substitution of HCFC-X (lifetime 15 years, ODP-value 0.1) this level would never be

reached. These two cases are illustrative of the negative ozone implications of the substitution of HCFC-X. The equivalent substitution of HCFC-Y has less impact on atmospheric chlorine because of the shorter atmospheric lifetime of 5 years. However, the best substitute with respect to ozone is the alternative HFC-Z (lifetime 30 years, ODP value 0), which enable the 2 ppbv to be reached in 2070 (30 years before it would be achieved in the first case), this date being the same as in the reference case (Table 10.5).

Climate - Figure 10.15b depicts direct halocarbon forcing and overall halocarbon

Figure 10.15b: Direct halocarbon radiative forcing and overall halocarbon forcing (including the stratospheric ozone depletion feedback) for different policies for the substitution by HCFC-X, HCFC-Y, and HFC-Z (option 5).

(dark shaded area indicates where 0.2 Wm^{-2} target of direct halocarbon forcing is exceeded and light shaded area where indicates 0.2 Wm^{-2} target of overall halocarbon forcing is exceeded).

① direct radiative forcing
 ② overall radiative forcing
 — sub X, 50%
 --- sub X, 30%, Y, 10%, Z, 10%
 - - - reference case
 - - - sub Y, 50%
 - - - sub Z, 50%

forcing (including the stratospheric-ozone-depletion feedback). Direct radiative forcing decreases in all cases for the period 1990-2100, except in that of substitution by HFC-Z, while, with the same exception, overall halocarbon forcing for all cases increases over the same period. In the case of substitution by HFC-Z (GWP value 3000), direct radiative forcing stabilizes at about 0.35 Wm^{-2} by 2100, an increase of about 0.1 Wm^{-2} on the simulated 1990 direct forcing level of 0.25 Wm^{-2} . In this HFC-Z case, incorporation of the feedback implies an increase in overall radiative forcing from 0.14 Wm^{-2} in 1990 to about 0.35 Wm^{-2} by 2100 (moderate halocarbon-climate risk). The difference in magnitude is a result of the decrease in (negative) ozone forcing (associated with decreasing atmospheric chlorine concentrations) over that period.

Figure 10.15c depicts the chlorine concentration and direct halocarbon forcing in a single graph (hereafter to be referred as the ozone risk figure), combining the information from Figures 10.15a and 10.15b. In this ozone risk figure, chlorine level is plotted as a function of overall halocarbon forcing. Furthermore, ozone risk areas are also depicted, together with the (tentatively) identified halocarbon-climate risk areas. The six climate/ozone risk areas are now defined as: a maximum ozone and moderate halocarbon-climate risk area ($>3 \text{ ppbv}$ and $>0.2 \text{ Wm}^{-2}$);

a maximum ozone and low halocarbon-climate risk area ($>3 \text{ ppbv}$ and $<0.2 \text{ Wm}^{-2}$); a high ozone and moderate halocarbon-climate risk area (>2 and $<3 \text{ ppbv}$ and $>0.2 \text{ Wm}^{-2}$); a high ozone and low halocarbon-climate risk area (>2 and $<3 \text{ ppbv}$ and $<0.2 \text{ Wm}^{-2}$); a low/moderate ozone and moderate halocarbon-climate risk area ($<2 \text{ ppbv}$ and $>0.2 \text{ Wm}^{-2}$); and finally, a low/moderate ozone and low halocarbon-climate risk area ($<3 \text{ ppbv}$ and $<0.2 \text{ Wm}^{-2}$). This Figure indicates the potential ozone and halocarbon-climate risks, and shows ozone risks are high in the first two cases (sub. X, 30%; Y, 10%; Z, 10% and HCFC-X, 50%). The third case, i.e. substitution by compound HCFC-Y, is the best option with respect to climate and ozone implications. Although substitution by HFC-Z is associated with low ozone risks (the chlorine level drops to the 2 ppbv-level by 2070), it certainly induces moderate halocarbon-climate risks in the second half of the next century.

The role of substitutes is thus of considerable importance. Continued and/or growing use of alternatives with relatively high ODPs and GWPs could have major impacts, in particular extension of the period of high ozone risks ($>2 \text{ ppbv}$). With respect to climate change special attention should be paid to those HFCs which have long atmospheric lifetimes and relatively high GWPs.

Figure 10.15c: Different policies for the substitution by HCFC-X, HCFC-Y, and HFC-Z related to ozone and climate targets (option 5).

- I maximum ozone risk and moderate halocarbon climate risks
- II maximum ozone risk and low halocarbon climate risks
- III high ozone risk and moderate halocarbon climate risks
- IV high ozone risk and low halocarbon climate risks
- V low/moderate ozone risk and moderate halocarbon climate risks
- VI low/moderate ozone risk and low halocarbon climate risks

- sub X, 50%
- - - sub X, 30%, Y, 10%, Z, 10%
- ... reference case
- sub Y, 50%
- sub Z, 50%

Question 6: What would the effect of an accelerated phase-out of all halocarbons, as envisaged in the Copenhagen Amendments, or a unanimous and complete 1995 phase-out be?

In 1992, the London Amendments were rendered more stringent by international agreement in Copenhagen (the Copenhagen Amendments). The new targets were set as follows:

- (i) CFCs : 75% reduction by 1994; and 100% by 1996.
- (ii) CCl_4 : 85% reduction by 1995; and 100% by 1996.
- (iii) CH_3CCl_3 : 50% reduction by 1994; and 100% by 1996.
- (iv) Halons : 100% reduction by 1994.
- (v) HCFCs: by 1996, the level of consumption (calculated in ODP tonnes) is to be limited to the sum of calculated 1989 HCFC consumption plus a 3% of calculated 1989 CFC consumption. The phasing-out of the alternatives employed would proceed in four steps; 35% reduction by 2005; 65% by 2010; 90% by 2015, and 100% by 2020.

In parallel with the Copenhagen Amendments, a theoretical case involving phasing out all currently used halocarbons as soon as possible (by 1995) is constructed. Such an ideal phase-out (case of maximum effort) would involve the full participation of

all countries (see option 1), phase-out of the currently-regulated halocarbons occurring by 1995, and of HCFC-22 by 2000 (option 4). The case of a complete 1995 phase-out, as described in option 3, is supplemented by a phase-out of the production of the alternatives by 2020 (making this case consistent with the Copenhagen Amendments). This maximum effort case is likely not technically feasible, and should be seen as a theoretical exercise. The assumed reduction scheme for this case is as follows (case of phase-out 1995, option 3): 75% reduction by 1993 (CFCs); 85% by 1994 (CCl_4); and 50% by 1993 (CH_3CCl_3) (all regulated fully halogenated halocarbons, 1 year earlier than the reduction scheme for these compounds envisaged in the Copenhagen Amendments). Phase-out of the alternatives (including HCFC-22), involved increasing production levels (3% annually until 1995), and 100% reduction by 2000 (HCFC-22), while other alternatives were undergo a 50% reduction by 2000, a 75% reduction by 2005, and a 100% reduction by 2020 (other alternatives).

Ozone - Figure 10.16a shows the chlorine concentration for the Copenhagen Amendments and maximum effort case. In both cases, peak chlorine loading is about 5% lower than in the reference case. The Copenhagen Amendments imply that the chlorine level reaches the 3 ppbv-level in 2020, and the 2 ppbv-level in 2060, which is

Figure 10.16a: Atmospheric chlorine concentration for the Copenhagen Amendments and the case of maximum effort (option 6).

(dark shaded area indicates maximum ozone risks where 3 ppbv target of atmospheric chlorine loading is exceeded, light shaded area indicates high ozone risks where 2 ppbv target of chlorine loading is exceeded).

--- reference case
 — Copenhagen Amendments
 - - - maximum effort

Figure 10.16b: Direct halocarbon radiative forcing and overall halocarbon forcing (including the stratospheric ozone depletion feedback) for the Copenhagen Amendments and the case of maximum effort (option 6).

(dark shaded area indicates where 0.2 Wm^{-2} target of direct halocarbon forcing is exceeded and light shaded area indicates where 0.2 Wm^{-2} target of overall halocarbon forcing is exceeded).

- ① direct radiative forcing
- ② overall radiative forcing
- reference case
- Copenhagen Amendments
- ... maximum effort

20 years and 10 years, respectively, earlier than in the reference case. Nevertheless, this still means accepting maximum ozone risks until the third decade of the 21st century. In the maximum effort case of a involving a ban on all halocarbons as soon as possible, the 2-ppbv and 3-ppbv targets are again achieved earlier, namely 10 years sooner, and the period of maximum ozone risks is now reduced to twenty years. Moreover, accumulated chlorine loading is now reduced by 35% vis-à-vis the Copenhagen Amendments, and by 65% compared to the London Amendments. In both cases, decreases in future stratospheric ozone losses, or even a recovery to former levels, is to be expected in the next century.

Analysis of the separate influence of the two additional measures (no-grace period, and phasing-out of other alternatives by 2020), compared to the complete 1995 phase-out (option 3), reveals that the omission of a period no-grace period for the developing world is of special importance.

Climate - In these accelerated phase-out scenarios, direct halocarbon forcing can only decrease, while overall halocarbon forcing (including the stratospheric-ozone-depletion feedback) stabilises at a level marginally above present levels (Figure 10.16b). Both scenarios are regarded as being low halocarbon-climate risk scenarios.

Question 7: What would the impact of the halons on bromine loading be in the case of limited compliance with the London Amendments?

By analogy to the assessment of option 1, the impact of the incomplete phase-out of the halons is examined. The difference between the four cases examined is the degree of compliance to the London Amendments: participation 100% (reference), 90%, 80% and 50%. The consumption of the non-complying countries is assumed to remain at the present levels.

Ozone - Figure 10.17a shows that in the case of 90-100% compliance atmospheric bromine levels decrease to 16 pptv by 2100 (reference case) and to 19 pptv (participation 90%). In the case of a 80% participation, bromine more or less stabilizes at the 1990-level. Figure 10.17b traces the atmospheric chlorine-equivalent concentration (the Cl-value plus 40 times the Br-value) for the four cases, a calculation based on the assumption that a bromine atom is 40 times as effective in depleting stratospheric ozone than a chlorine atom (Prather *et al.*, 1992). With the exception of the 50% compliance case, the options differ only marginally, a finding which once again illustrates the minor role of the brominated chemicals in the current ozone policy.

Climate - The impact of the bromine

Figure 10.17a: Atmospheric bromine concentration for different levels of participation of the London Amendments (only related to the halons) (option 7).

compounds is negligible because of their low concentrations.

10.7 Discussion and conclusions

The most important implications of halocarbon emissions are their effects on stratospheric ozone, as observed in the last decade in the form of ozone decreases in the middle and high latitudes in both hemispheres, and the massive ozone losses over Antarctica. Insofar as climate change is concerned, the halocarbons play a role through their direct

radiative effects, but also via their indirect radiative effects (the negative radiative impact induced by ozone losses). Overall halocarbon forcing exhibits large latitudinal differences, varying from positive (around the equator) to negative (at the poles), which is mainly due to geographical variability in indirect radiative effects (linked with ozone depletions). At the poles, overall radiative forcing could even counteract a significant fraction of the positive radiative forcing caused by the non-halocarbon greenhouse gases. Globally averaged (negative) indirect radiative forcing is about 80% of the

Figure 10.17b: Atmospheric chlorine equivalent concentration for different levels of participation of the London Amendments (only related to the halons) (option 7).

(dark shaded area indicates maximum ozone risks, where the atmospheric chlorine equivalent loading of 3 ppbv is exceeded, light shaded area indicates high ozone risks, where 2 ppbv-level is exceeded).

(positive) direct radiative forcing.

In this study, various policies pertaining to the future production of halocarbons are analysed with respect to their implications for the atmospheric chlorine concentration (which affects stratospheric ozone depletion) and for direct and overall halocarbon forcing (which have a bearing on the climate change problem). These scenarios are all variations of the reference scenario introduced by the WMO (1992), which incorporates the best estimates of future chlorine/bromine emissions, assuming full compliance with the London Amendments, and a phase-out of HCFC-22 emissions by 2040. Simulations run on the halocarbon model show that for this WMO reference scenario, atmospheric chlorine concentration remains above the 3 ppbv level (chlorine abundance in 1985) until approximately 2040, with a peak chlorine level of some 4 ppbv (10-15% higher than the 1990 level). This shows that a complete phase-out according to the London Amendments is not sufficient to avoid maximum ozone risks during the first four decades of the 21st century. In that period, the currently-observed ozone losses will continue and can even accelerate. In the reference case, the atmospheric chlorine concentration reaches the 2 ppbv level in the second half of the next century, around the year 2070, this level being that necessary for recovery of the Antarctic ozone hole. Two ppbv is therefore seen as the 'no effect' level, and represents a sustainable ozone target. Model simulations demonstrate that in order to achieve the 2 ppbv, and the 3 ppbv, level earlier, and thus mitigate the risks associated with ozone depletion, the following options are available in order of efficacy:

1. an accelerated phase-out of the currently-regulated halocarbons by the year 1995 in the industrialized world;
2. full compliance with the London Amendments by the developing world;
3. a phase-out of HCFC-22 before the year 2000 in the industrialized world, and in the developing world ten years later.

The effect of the first two options, taken together, would be a 5% reduction in the

peak level of atmospheric chlorine, and a curtailment of the period associated with maximum ozone risks (chlorine level above 3 ppbv) by 10 years. The third option leads to a further reduction of this period by a further ten years. The period associated with high, though not maximum, ozone risks (chlorine level above 2 ppbv) is reduced by ten years as a result of this accelerated phase-out, and would be expected to end around the year 2060. The reduction scheme envisaged in the present Copenhagen Amendments (phase-out by 1996) is comparable with such an accelerated policy, although according to this agreement the timing of the phase-out of HCFC-22 is later (by 2020), and for the other alternatives sooner (by 2020, compared to 2040 in the accelerated policy). While for both policies, the 2 ppbv and 3 ppbv dates are about the same, the accumulated atmospheric chlorine loading is nevertheless about 20% higher under the Copenhagen Amendments, which is a result of the time-delay between the phase-out dates of the regulated halocarbons and HCFC-22 in the two policies.

Additional measures aimed at abolishing the transition period of a temporary application of alternative compounds, HCFCs and HFCs, would bring the achievement of the 2 ppbv and 3 ppbv target levels forward by a further ten years.

Unlike the ozone risks for the next decades, which remain high, the halocarbon-climate risks associated with both the London Amendments and this accelerated phase-out scenario remain low. Nevertheless, the stratospheric-ozone-depletion feedback results lead to an interesting implication. It transpires that an (accelerated) phase-out of the halocarbons leads to a small increase in overall halocarbon forcing over the period 1990-2100, and thus has negative implications for the climate change problem. The order of magnitude of this effect is, however, rather small (less than 0.1 Wm^{-2}). In reality, the London Amendments, although signed by most key nations, have still not been signed by a number of countries (mainly from the developing world).

Based on model calculations this study examines a number of currently feasible dev-

elopments in halocarbon production, which affects the duration of the time period with associated maximum/high ozone risks:

- a. stabilisation/growth of the production of long-life CFCs in the non-complying countries (mainly the developing world) results in maximum ozone risks for the entire 21st century;
- b. partial compliance with the London Amendments; less than 90% compliance in itself implies maximum/high ozone risks for the entire 21st century;
- c. delayed scheduling of the world-wide phase-out of the currently-regulated halocarbons to approximately the year 2010; maximum ozone risks until 2050 with a peak of chlorine loading which is 10% higher than the peak value envisaged in the London Amendments;
- d. delayed phase-out to the year 2040 in the developing world; maximum ozone risks until approximately 2050, with ozone risks remaining high until approximately the year 2090.

The halocarbon-climate risks associated with all of these developments are likewise low.

However, even under full compliance with the London Amendments, negative ozone implications might be expected to result from the use of HCFC-22 or similar compounds as substitutes for the eliminated CFCs, especially if the demand for such chemicals further increases after the completion of the substitution process. This state of affairs is simulated in a further option which would also lead to maximum ozone risks throughout the next century:

- e. increasing production of HCFC-22; maxi-

mum ozone risks remain until around 2070, after which they are still high.

The production of HCFC-22 should therefore be eliminated at the beginning of the next century (third option in accelerated phase-out). In place of this chemical, the temporary application of alternative compounds, specifically of HCFCs and HFCs with lower ODP and GWP values than HCFC-22 should be preferred. An increase in the consumption of these alternative compounds, once the substitution process has been completed by the beginning of the next century, could still have important implications not fully for the ozone problem, but also for climate change. Overall radiative forcing (about 0.15 Wm^{-2} in 1990) will in that case even exceed the 0.2 Wm^{-2} level (the direct halocarbon forcing level of the mid-1980s) by 2100. With respect to the latter risk, special attention should be paid to the HFCs (zero ODP) with long atmospheric lifetimes and a relatively high GWP.

- f. increasing production of the alternatives HCFCs after the substitution process leads to maximum ozone risks up to the year 2050, and afterwards high ozone risk;

- g. increasing production of the HFCs (zero ODP) results in no extra ozone risk, but in moderate halocarbon-climate risks after approximately the year 2050.

Finally, this study has also evaluated the ozone implications of the IPCC scenarios. Since none of these scenarios envisaged the achievement of the 3 ppbv-level, they were deemed to be maximum ozone risk scenarios.

11 Stabilizing atmospheric greenhouse gas concentrations: towards low climate risk levels

This Chapter is based on: Rotmans, J., and Elzen, M.G.J. den (1993a): Halting Global Warming: Should Fossil Fuels be phased out?, In: Halting Global Warming: concern for tomorrow, M. Lal (Ed.), Tata McGraw-Hill Publishing Company Limited, New Delhi, India.

11.1 Introduction

Within a relatively short time, global climate change has become a major scientific and political issue, which has captured a prominent position on political agendas. In 1987, at workshops in Villach and Bellagio, an international group of experts reviewed possible policies for a range of environmental problems associated with climate change (Jäger, 1987). In 1988, at the Conference on the Changing Atmosphere in Toronto (WMO, 1988), scientists and policy makers formulated several recommendations, including a quantitative call for a 20% CO₂ emission reduction in 2005, followed by a global reduction of 50% around 2025, which would be sufficient to stabilize atmospheric concentrations (Environment Canada, 1988). In July 1988, WMO, UNEP and ICSU established the Advisory Group on Greenhouse Gases (AGGG), which had as primary task to prepare a report on 'the full range of responses to anticipated climatic change'. Within the framework of AGGG, Working Group II was set up to identify targets and indicators of climate change (AGGG, 1990c). Parallel to this, in November 1988 the IPCC was established by WMO and UNEP to provide a mechanism for scientific and political discussions and policy preparation (Nitze, 1989). Within this framework Working Group III was set up to consider response strategies.

In the course of time the results of the AGGG study were intended to complement the activities of the IPCC, providing valuable supplementary information to the inter-

national policy discussion. Yet under heavy time pressure all these activities were not adequately matched to each other. One example amongst others is the design of the four IPCC-1990 scenarios by the Response Strategies Working Group of the IPCC, which were originally meant to be restrictive (related to the timing of a doubling of CO₂-equivalent concentration) (IPCC, 1991b). The problems with these scenarios, however, is that they are not related to long-term environmental goals with respect to climate change as identified by AGGG (1990c). Even the lowest scenario would lead to global mean temperature increases that are unprecedented in the last 100,000 years and more.

In this Chapter the IPCC-1990 scenarios are evaluated from the risk minimization perspective of sustainable development, by connecting the scenario defined by the IPCC with the long-term climate change targets formulated by the AGGG. The same has been done for the updated six IPCC-1992 scenarios (hereafter IS92a-f scenarios), which are more comprehensive and, methodologically, more soundly based than the IPCC-1990 scenarios (Pepper *et al.*, 1992; Leggett *et al.*, 1992) (see also Chapter 5).

The structure of this Chapter is as follows. After describing the role of fossil fuels in global climate change (section 11.2), section 11.3 deals with sustainable targets which might be used for evaluating long-term climate strategies. Then it is demonstrated in what way IMAGE (experimental version 1.6) can be used to develop a scenario that complies with the sustainable targets as defi-

ned by AGGG. This scenario, which is called Low-Risk scenario, involves a shift from fossil fuels to renewable energy sources. The feasibility of such an approach, which would limit climate change risks sufficiently, is also described here. Finally, a delayed response analysis is performed to show that the timing of the response is of crucial importance.

11.2 Role of fossil fuels in global climate change

11.2.1 Introduction

During the past century the concentrations of greenhouse gases in the atmosphere has increased steadily as for a long time the anthropogenic emissions have exceeded the natural absorption capacity. *Figure 12.1* illustrates the global emission path of CO_2 from fossil fuel combustion since 1860. As the emissions are related to fundamental human needs (energy, comfort and food) there is a clear link between the emissions of greenhouse gases and the growth of population, production and consumption. Energy-related emissions have fallen since the energy crisis years 1973 and 1980, but they have risen since 1985 due to the low energy prices and the continuing growth of production and consumption. The use of fossil fuel is the most important source of CO_2 emissions.

Figure 12.2 gives the global emissions of CO_2 from 1950. The emissions due to coal are about twice those of natural gas for the same amount of energy (oil-related emissions are about one and a half times as much). In 1989 and 1990, the global emission was about 6.0 ± 0.5 billion tonnes of carbon (Marland and Boden, 1991). At present the destruction of tropical forests releases about 1.6 ± 1.0 billion tonnes of carbon (Watson *et al.*, 1992). Methane from fossil origins is released by the exploitation of coal and oil if it cannot be used or flared and also by the distribution of natural gas. Methane, as a product of the anaerobic digestion of organic material, is also released from landfills, wetlands, rice paddies and by fermentation in the rumen of ruminants. Nitrous oxide is mostly produced by denitrification processes in environments with a high nitrogen load such as soil and polluted water. This substance is also released in limited quantities by the use of fossil fuels.

11.2.2 Role of energy-related greenhouse gas emissions

The exploration and use of fossil fuels causes emissions of CO_2 , CO, hydrocarbons, and nitrogen compounds (N_2O , NO_x). Dependent on the assumptions and definitions, it can generally be said that the agricultural and industrial sector causes 35% of the problem,

Figure 11.1: Global CO_2 emissions from fossil fuel combustion (Rotty and Marland, 1986; Marland, 1989; Marland and Boden, 1991).

Figure 11.2 Global CO₂ emissions from fossil fuel combustion since 1950 (Marland *et al.*, 1988).

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 (Figure 11.3). 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. Emissions of CO₂ from fossil fuel combustion are reasonably well-known, since they are based on well known data of the consumption of the major fossil fuels (oil, gas and coal). Uncertainties in the present estimates of emission of CO₂ are relatively small, about 5%. They arise from uncer-

tainties about consumption, from the variability of emission factors and from uncertainties about the rate of flaring at fossil fuel production sites (Okken *et al.*, 1989). The emissions of CO₂ from fossil fuel combustion contribute approximately 50% to the enhanced greenhouse effect. The remaining 15% of the total 65% that the energy sector accounts for is caused by non-CO₂ emissions. As for 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).

Figure 11.3 Relative contribution to climate change

The uncertainties in the present estimates of energy related emissions of methane, approximately 20% of anthropogenic methane emissions, are much larger than for CO₂. This is mainly due to uncertainties about coal production, the average methane emission of mined coal, rate of loss or throughput of methane and finally a lack of field data (EPA, 1990). Nitrous oxide is also emitted by combustion of fossil fuels, although a recent study has shown that previous estimates were too high because of a recently found sampling artefact (Muzio and Kramlich, 1988). The re-examination of old emission data indicates that N₂O emissions from these sources are ten times lower than those reported previously (de Soete, 1990).

Carbon monoxide plays an essential role in the global CH₄-CO-OH cycle (Rotmans *et al.*, 1990). The magnitude of the uncertainties in the carbon monoxide budget is even larger than for methane. 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 (O₃), which also acts as a greenhouse gas.

11.3 A sustainable climate response strategy

11.3.1 Quantitative targets for climate strategies

One way of developing sustainable criteria for climatological changes is to derive quantitative targets from maximum tolerable rates at which ecosystems can adapt to changes in temperature and precipitation patterns. Present scientific knowledge indicates that the natural limit of the migration rate of ecosystems is around 50 km per century. At a workshop in Bellagio (Jäger, 1987) it was suggested to take a global rate of temperature of 0.1 °C per decade as an initial target value, which would allow for adaptation of ecosystems. Krause *et al.* (1989) have proposed the same standard for sustainability of 0.1 °C temperature rise per decade. The Working Group 'Targets and Indicators' of

the AGGG also recommended a maximum rate of global mean temperature change of 0.1 °C per decade, together with a maximum global mean temperature increase of 2 °C above pre-industrial global mean temperature (AGGG, 1990c). An absolute temperature limit of 2 °C 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. These values are consistent with estimates of maximum natural climate variations in the past according to Sassini *et al.* (1988), who evaluated past rates of temperatures and absolute changes from ice core temperature records. Since no past evidence appears to be available for faster temperature changes than approximately 0.1 °C per decade, this is used here as a reference value for a climate policy of risk minimization.

In a similar way provisional limits for the rates and magnitude of sea-level rise could be set to prevent damage to coastal areas, wetlands and coral reefs. A 2-5 cm rise in sea-level per decade and a maximum sea-level rise of between 0.2 and 0.5 m above the 1990 global mean sea-level was recommended by the Working Group 'Targets and Indicators' of AGGG (AGGG, 1990c). All these targets must be periodically reviewed in light of feedbacks and non-linearities that may introduce surprises and unexpected changes. Another problem with these targets is that they are global, while large regional differences may arise from global temperature and sea-level rise patterns. This underscores that there is an urgent need for regionally based targets, but, given the basic gaps in our knowledge about regional effects of climate change, these regional targets are not yet available.

Other targets have been suggested by Swart *et al.* (1989), such as atmospheric concentrations of greenhouse gases which can serve as a monitoring instrument and as a basis for possible adjustments of emission control policies. This study restricts itself to the temperature and sea-level rise targets: in the following the target rates and levels of 0.1 °C per decade (*relative temperature target*) and 2 °C above pre-industrial (*absolute*

Figure 11.4a: Temperature increase for the four IPCC-1990 scenarios over the period 1900 to 2100.

(shaded area indicates where the absolute temperature target of 2 °C is exceeded).

- IPCC-1990 Business-as-Usual scenario
- - - IPCC-1990 Low emissions scenario
- ... IPCC-1990 Control Policies scenario
- . - . IPCC-1990 Accelerated Policies scenario

temperature target) for global mean temperature rise, and 2-5 cm per decade (*relative sea-level target*) and 20-50 cm above 1990 level (*absolute sea-level target*) for global mean sea-level rise are used.

Here the present IPCC-1990 scenarios are evaluated from the perspective of sustainable development, by coupling these scenarios with the target values set above for the rates and levels of global mean temperature and sea-level change. In this context, an emission scenario is called less sustainable if the anticipated global mean temperature and sea-level rise does exceed these targets more and

longer for a period of time. A future in which these targets are met is sustainable in the sense that they reflect a world in which the anticipated risks of climate change tend to acceptable levels. In Figures 11.4a and 11.4b the resulting relative and absolute global mean temperature effects of the four IPCC-1990 scenarios, with a best guess IPCC-value of the climate sensitivity of 2.5 °C (Houghton *et al.*, 1990; 1992), are related to the relative and absolute temperature standards. The information coming from Figures 11.4a and 11.4b is now translated into a picture that combines rates and absolute

Figure 11.4b: Rate of temperature increase for the four IPCC-1990 scenarios over the period 1900 to 2100.

(shaded area indicates where the relative temperature target of 0.1 °C per decade is exceeded).

- IPCC-1990 Business-as-Usual scenario
- - - IPCC-1990 Low emissions scenario
- ... IPCC-1990 Control Policies scenario
- . - . IPCC-1990 Accelerated Policies scenario

levels of temperature increases (Figure 11.4c). Here, the rate of global temperature (per decade) is given as a function of the absolute temperature rise. Furthermore four climate risk areas are defined which indicate the potential climate risk with respect to temperature increase: a maximum risk area ($>2^{\circ}\text{C}$ and $>0.1^{\circ}\text{C}$ per decade), a high risk area ($<2^{\circ}\text{C}$ and $>0.1^{\circ}\text{C}$ per decade), a moderate risk area ($>2^{\circ}\text{C}$ and $<0.1^{\circ}\text{C}$ per decade), and a low risk area ($<2^{\circ}\text{C}$ and $<0.1^{\circ}\text{C}$ per decade). This picture shows that the IPCC-1990 Business-as-Usual (BaU90) scenario and the Low Emissions scenario are associated with high and maximum climate risk (BaU90 scenario enters the maximum risk by 2035 and IPCC-1990 Low Emissions scenario by 2055), the IPCC-1990 Control Policies scenario tends to moderate risk (after 2070), while the IPCC-1990 Accelerated Policies (AP90) scenario is a moderate to low climate risk scenario. The results indicate that according to all IPCC-1990 scenarios the standards for sustainability, defined above, will be exceeded. Even in the AP90 scenario the relative temperature target of 0.1°C per decade will be exceeded from 1960 to 2035. From this Figure two things can be learned. First, that it is impossible to avoid a rise in temperature due to past emissions of greenhouse gases, and second, that there is a need for an even more strict scenario that complies with the above-mentioned rates and levels of temperature and sea-level change.

11.3.2 Low-Risk scenario

Main features

As even the lowest IPCC-1990 scenario, the AP90 scenario, would lead to global mean temperature increases that are unprecedented in the last 100,000 of years, an alternative scenario is developed, called the Low-Risk scenario, which adheres to the targets for sustainability discussed above. Basic philosophy behind the Low-Risk scenario is that, in order to meet these targets, the CO_2 -equivalent concentration should be stabilized at the lowest possible level, in the shortest possible time. Stabilization of the CO_2 -equivalent concentration at present-day levels is not very feasible, because of the long atmospheric lifetimes of gases such as carbon dioxide, nitrous oxide and CFCs.

For CO_2 , the Low-Risk scenario assumes future global emission reductions which are more or less consistent with the Toronto guidelines: a 20% reduction by 2005 and 50% by 2025, relative to 1988 (WMO, 1988). To stabilize the atmospheric methane concentrations well below present-day levels the methane emissions are reduced with 15% by 2025 and 20% by 2100, combined with a stabilization of the total (direct sources and oxidation parts) carbon monoxide emissions (Rotmans *et al.*, 1992). Anthropogenic emissions of nitrous oxide are reduced gradually

Figure 11.4c: Four IPCC-1990 scenarios related to absolute and relative temperature target levels.

- I maximum risk
- II high risk
- III moderate risk
- IV low risk
- IPCC-1990 Business-as-Usual scenario
- - - IPCC-1990 Low emission scenario
- ... IPCC-1990 Control Policies scenario
- . - . IPCC-1990 Accelerated Policies scenario

by 30% (10% of the total emissions) to slow down the increasing trend of the atmospheric concentration of nitrous oxide. Reversing the increasing trend of atmospheric nitrous oxide is not feasible in the short term, because of the long atmospheric residence time. For CFCs a total phase-out following the London Amendments is assumed.

It should be noted that if climate induced positive feedbacks on the emissions or concentrations of greenhouse gases do materialize, the above-mentioned controls will not be sufficient. For methane, for instance, the atmospheric concentrations might turn out to be 60% higher by 2100 if biogeochemical feedbacks on the emissions of methane would materialize (Rotmans *et al.*, 1992).

Backgrounds

What kind of world would meet the requirements of the Low-Risk scenario? Below some brief indications are given, how the emissions scenario that fulfilled the climate change requirements is obtained. The world population is expected to approach 11.33 billion in 2100 according to recent analysis by the World Bank (1991). Concern about the global environment will lead to a change in lifestyle in the developed world, resulting in a decrease of fossil-fuel consumption through energy conservation improvements in efficiency and a shift to non-carbonaceous fuels both in developed and developing countries. This will lead to a low per capita energy consumption of fossil fuels rather than the introduction of expensive emission control technologies. While, assuming an annual per capita economic growth rate of 1.7% in the developed world and 2.9% in the developing countries, the most important policies would include: annually increasing the end-use efficiency of 1.5% in the industrialized world and 1.8% in the third world, while at the same time solar energy is stimulated (reducing the costs to US \$ 10/GJ within 40 years), while production of synfuels prevented by high non-energy costs and environmental taxes on end-use are gradually introduced proportional to the carbon content of the fuel type. Compared to the present situation, coal is fully phased out, oil supply

is more or less stable, but the major part of the growth of the energy demand (moderated by large efficiency increases) is captured by renewables. The final implication of a CO₂-emission reduction strategy would be a shift away from fossil fuels, implying that the available resources will not be fully used. Deforestation is assumed to be reversed, among other means by increasing the intensity of agriculture and forestry and large reforestation efforts (the same deforestation assumptions as in the AP90 scenario). In the industrial countries the CO₂-emission in 2025 should be about 80% below those in 1990, according to the Low-Risk scenario.

Measures directed towards control of CO₂, such as energy efficiency increases, a shift to non carbonaceous fuels and arrest of deforestation will also contribute to the control of methane and carbon monoxide and, to a lesser extent nitrous oxide. In addition, a large number of conventional emission control measures are available to limit the emissions of methane and carbon monoxide. This especially applies to the energy sector, which contributes 20 to 40% to the direct methane emissions, since point sources are easier to manage than agricultural sources (Rotmans *et al.*, 1992). In the Low-Risk scenario methane emissions are assumed to be decreased by increasing recovery of methane losses at coal mining sites and landfills, by control of gas losses during exploration and production of oil and gas by improved management, maintenance and training, and by localisation and control of leakages from natural gas transportation and gas distribution. The releases of methane from cattle can be reduced by increasing the efficiency of the production, especially through changes in feeding practices in the developing countries, and by limiting the consumption of meat and dairy in the industrialized countries (Rotmans *et al.*, 1992). Anthropogenic CO-emissions are limited by introducing CO-emission standards for automobiles, by introducing modern efficient production technologies in the steel industry, and by improving the efficiency of residential heating practices, primarily in Eastern Europe.

N₂O-emissions from fertilizer application

are reduced by a controlled growth of fertilizer use in the developing world versus a sharp decrease of fertilizer use in the developed world enabled by modifications in agricultural practices; energy related emissions of N_2O are assumed to be minimized by technological measures, while emissions of nitrous oxide from deforestation are stopped through proper forest management and reforestation.

For CFCs it is assumed that the London amendments of the Montreal Protocol, which form a stringent update of the Montreal Protocol, are fully implemented. It is assumed that 30% of the alternatives will be replaced by alternatives (HCFCs and HFCs). Besides the production of these alternatives is growing with 2.5% annually till 2020, and then phased out by the year 2040. In *Table 11.1* the main assumptions of the Low-Risk scenario are presented in more detail.

11.4 Results

This section analyses the implications of the IPCC-1992 scenarios and the Low Risk scenario for future greenhouse gas concentrations, radiative forcing, and finally global mean temperature and sea-level rise, for which the latter two are related with the temperature and sea level rise targets as defined above. This has been done by incorporating

these scenarios in IMAGE (experimental version 1.6), and running the model in two modes: the base-case mode (no stratospheric-ozone-depletion feedback and no methane feedbacks), and the feedback mode (the various feedback parameters are set at their central estimate values). Only if the model is run in the feedback mode, this will be explicitly mentioned as FB mode.

Carbon dioxide For the calculations of the future atmospheric CO_2 -concentrations for the IPCC-1992 scenarios, the same scenario assumptions are used as those made by the IPCC (Pepper *et al.*, 1992). The fossil fuel inputs are equal to the IPCC-values, while the socio-economic assumptions in the land use change model (Rotmans and Swart, 1991) are such, that the deforestation trend is comparable with the IPCC-1992 deforestation trends, as described in Pepper *et al.* (1992). The deforestation assumptions for the IS92a-c scenarios, and IS92e-f scenarios are the same as for the IPCC-1990 Business-as-Usual (BaU90) scenario, while for the IS92d scenario the assumptions of the IPCC-1990 Accelerated Policies (AP90) scenario (and Low Risk scenario) are used. In the land use change model the data for the average carbon content in above-ground biomass and in the soils are equal to those used by Pepper *et al.* (1992), which are based on OECD (1991). *Figure 11.5* compares the resulting

Figure 11.5: Net CO_2 emissions from deforestation for the six IPCC-1992 scenarios and the Low-Risk scenario over the period 1990 to 2100. (trends for IS92c and IS92f scenario are not shown, to avoid confusion).

Table 11.1: Description of the Low-Risk scenario (Rotmans and den Elzen, 1993a)

Low-Risk scenario			
CO ₂		CH ₄	
Energy Supply	Energy consumption is primarily the same as in the AP90 scenario. Coal is fully phased out, oil supply is more or less stable, but major part of the energy demand growth is captured by renewables.	Energy	Methane emissions from energy sector decrease due to decrease in energy consumption, till 65% of present level in 2100.
		Landfills	Methane emissions from land fills decrease due to technical improvements to recover methane releases.
Energy Demand	Large energy efficiency improvements compared to the AP90 scenario.	Rice paddies	Methane emissions from rice paddies continuously decrease by altering rice cultivation practices and rice cultivars to 70% of present level.
Emission	CO ₂ emissions due to commercial energy decrease with 20% reduction by 2005 and by 50% by 2025.	Enteric fermentation	Methane emissions from cattle reduces by increasing the efficiency of the production, especially through feeding practices in the developing countries, and by limiting the consumption of meat and dairy in indus. countries.
Deforestation	Reforestation case; deforestation stops in 2025, and about 1000 million ha are reforested in 2100 Net CO ₂ -emissions are over the period 2025 till 2100 negative, -0.2 GtC in 2100.	CO	
		Energy	CO emissions from energy consumption and transport decrease by current emission control technologies on mobile and stationary sources (-110 Tg/yr or -60% in 2100).
		Deforestation	Carbon monoxide emissions from deforestation decrease with decreasing rates of deforestation (-135 Tg/yr or 100% in 2100).
N ₂ O		halocarbons	
Energy	N ₂ O emissions decreases under present level.	CFCs, CH ₃ CCl ₃ , CCl ₄ , and halons	London Amendments: complete phase-out for CFCs, CCl ₄ , and halons by 2000, and for CH ₃ CCl ₃ by 2005.
Fertilizer	N ₂ O emissions due fertilizer use is reduced due to controlled growth of fertilizer use in developing world versus a sharp decrease of fertilizer use in the industrialized countries.	HCFCs and HFCs	HCFC-X, 30% substitution; HCFC-Y, 10% substitution; HFC-Z, 10% substitution, starting in 1992, with a grow of 2.5%/yr till 2020, and then phase-out by 2040.
Biomass burning	N ₂ O emissions from biomass burning decreases (-0.5Tg/yr or -35% in 2100).		

net CO₂ emissions from deforestation for the IS92a,b,d,e scenarios with the IPCC-1992 values. The trends for IS92c,f scenarios are not shown in this Figure, to avoid confusion. The net CO₂ emissions for the IS92c scenario are somewhat lower than those of the

IS92a scenario due to a lower population growth (UN medium-low case), and for the IS92f scenario slightly higher due to a higher population growth (UN medium high case). The cumulative 1990-2100 difference with the trend of IS92a scenario is about 10% and

20% for the IS92c- and IS92f scenario, respectively. The differences between the simulated and the IPCC-1992 trends for all scenarios turn out to be small; the cumulated difference is less than 5% for all scenarios (or about 4 GtC for IS92a and IS92c, and 2 GtC for IS92d) (Pepper *et al.*, 1992).

In Figure 11.6 the resulting atmospheric CO₂ concentrations are depicted for the six IPCC-1992 scenarios, and the Low-Risk scenario, based on model calculations with the coupled carbon cycle/climate model (Rotmans and den Elzen, 1993b). The atmospheric CO₂-levels by 2100 differ from the BaU90 central CO₂-projection of 761 ppmv in 2100 (Elzen and Rotmans, 1993b), with about +30% for the maximum case (IS92e), and -30% for the minimum case (IS92c). These results are in contrast with those of the Low-Risk scenario, for which the atmospheric CO₂ concentration stabilizes at a level below 400 ppmv (+12% above current levels) during the second half of the next century. The radiative forcing changes due to CO₂ concentration changes over the period 1990-2100 are given in Table 11.2. The CO₂ forcing changes are comparable with the best guess values of Wigley and Raper (1992), which are also based on a balanced carbon cycle model and the same IPCC-1990 radiative forcing-atmospheric relationships of Shine *et al.* (1990) as in our study. The relative differences for the six IPCC-1992

scenarios between both studies are less than 5% (only for the IS92c scenario, about 9%).

Methane Figure 11.7 presents the atmospheric methane concentration projections for the six IPCC-1992 scenarios and the Low-Risk scenario, as calculated with the methane model in the base case mode (Rotmans *et al.*, 1992). Based on the criterion of equal future CH₄ emissions trajectories, the results of the IPCC-1992 scenarios can now be analysed in sets of two scenarios: IS92a,b; IS92c,d; and IS92e,f. Figure 11.7 clearly shows that the atmospheric CH₄ concentration does not only depend on the methane emissions (equal within a scenario-set), but also on the emissions of other gases which play a role in the oxidation processes, especially carbon monoxide, hydroxyl radical, nitrogen oxides and ozone depleting compounds. The results of the IS92a and IS92b scenarios (equal direct CO-emissions and NO_x-emissions) show the impact of the halocarbons on the atmospheric methane levels. A stricter policy for the CFCs, as assumed in the IS92b scenario (fully participated London Amendments), induces a recovery of the stratospheric ozone layer which leads to a decreased production of OH in the troposphere, and thus an increase in the atmospheric methane concentration. Comparing the results of the IS92c and IS92d scenarios demonstrates that control policies on the direct CO emissions,

Figure 11.6: Atmospheric CO₂ concentration for the six IPCC-1992 scenarios and the Low-Risk scenario over the period 1900 to 2100.

Figure 11.7: Atmospheric CH_4 concentration for the six IPCC-1992 scenarios and the Low-Risk scenario over the period 1900 to 2100.

offers a possibility of slowing down the increase of the atmospheric methane concentration. The 10% reduction of CO emissions by 2025 for the IS92d scenario leads to lower atmospheric methane levels than those of the IS92c scenario (slightly increasing CO emissions). The IS92f scenario bears out the impact of the combination of high direct CO emissions and halocarbon emissions (a non-fully participated London Amendments). Finally, the Low-Risk scenario (20% reduction of the methane emissions, combined with a stabilization of the direct CO-emissions by 2025; and fully participated London Amendments) leads to a stabilization of the CH_4 concentration at a level of about 1800 ppbv. Table 11.2 tabulates the radiative forcing changes due to methane concentration changes (including the indirect effects via stratospheric water vapour), which are for the IPCC-1992 scenarios 20-30% lower than Wigley and Raper's projections. This is a direct result of the increasing tropospheric lifetime of methane (+10-30%) due to the decreasing OH concentration trend over the period 1990-2100, as simulated by IMAGE.

Table 11.2 also gives the methane radiative forcing, if the temperature induced biogeochemical feedbacks on the methane emissions (wetlands, rice paddies, and hydrates) do materialize (feedback case), which are about 0.2 and 0.1 Wm^{-2} higher for

the IPCC-1992 scenarios and the Low Risk scenario, respectively, compared to the base case projections.

Nitrous oxide The simulated N_2O radiative forcing changes are 15-20% higher than those of Wigley and Raper (1992) (Table 11.2), which is a direct result of the higher atmospheric lifetime of 150 years used here (see Chapter 3) (Wigley and Raper, 1992) used a lifetime of 130 years). Both lifetimes fall into the uncertainty range of 110-168 years as given by WMO (1992).

Halocarbons The concentration projections for the CFCs, CCl_4 and CH_3CCl_3 for the IPCC-1992 scenarios are calculated by running the halocarbon model (Chapter 10) with the same IPCC-1992 scenario assumptions as described in Pepper *et al.* (1992). Because of the detailed emissions scenarios for the alternatives (HCFCs and HFCs), covering eight alternatives instead of the three imaginary compounds included in the halocarbon model, the emissions scenarios of these eight alternatives are directly incorporated in the halocarbon model. The concentration changes are now calculated using Equation (10.14) in Chapter 10, with the stratospheric lifetimes based on Prather *et al.* (1992), and the tropospheric lifetime hydroxyl concentration dependent. The latter dependency leads to significantly increasing tropospheric

Table 11.2: The radiative forcing changes, temperature targets, and sea-level rise targets for the IPCC-1992 scenarios and the Low Risk-scenario.

Parameter\scenario	Bau90	IS92a	IS92b	IS92c	IS92d	IS92e	IS92f	Low Risk
$\Delta Q(1990-2100)^1$ (Wm^{-2})								
CO ₂	4.68	4.60	4.41	2.20	2.90	6.31	5.40	0.72
CH ₄ (+H ₂ O) (nf/fb) ²	.83/1.05	1.0/1.2	1.1/1.3	.36/0.5	.05/0.2	1.0/1.2	1.4/1.6	0.1/0.2
N ₂ O	0.34	0.31	0.31	0.22	0.25	0.37	0.36	0.07
Halocarbons (nf/fb) ²	1.19/0.4	.28/0.3	.25/0.34	.28/0.3	.1/0.2	.1/0.25	.28/0.3	-.15/0
Total (base case)	7.0	6.2	6.1	3.1	3.2	7.7	7.5	0.7
Total (feedback case)	6.45	6.4	6.2	3.2	3.3	7.75	7.7	0.7
Temperature targets (base case)								
year at 2.0 °C	2045	2045	2045	2060	2070	2040	2040	-
year at 0.1 °C/decade	1960	1960	1960	1960- 2080	1960	1960	1960	1960- 2010
Sea-level rise targets (base case)								
year at 0.2 m	2000	2000	2000	2000	2000	2000	2000	2000
year at 0.5 m	2060	2060	2060	2080	2080	2060	2060	-
year at 2 cm/decade	1970	1970	1970	1970- 2100	1970	1970	1970	1970- 2045
year at 5 cm/decade	-	-	-	-	-	2025	2020	-

¹ $\Delta Q(1990-2100)$ is the total change in radiative forcing over the period 1990-2100 (Wm^{-2}). Over the period 1900-1990 the simulated radiative forcing is equal to 1.9 Wm^{-2} (base case) and 1.7 Wm^{-2} (feedback case) (CO₂: 1.10 Wm^{-2} ; CH₄ (+H₂O): 0.48 (nf)/0.45 (fb) Wm^{-2} ; N₂O: 0.07 Wm^{-2} ; halocarbons: 0.25 (nf)/0.14 (fb) Wm^{-2}).

² nf/fb (base case/feedback case): without and with the climate feedbacks on the methane emissions (wetlands, rice paddies, and hydrates) and the stratospheric-ozone-depletion feedback (indirect halocarbon forcing).

lifetimes (+10-20%) over the period 1990 till 2100 for all IPCC-1992 scenarios due to decreasing OH concentration trends. The resulting direct radiative forcing changes (Table 11.2) are between 0.1 and 0.15 Wm^{-2} lower than the estimates of Wigley and Raper (1992), as a direct result that their estimates include the radiative effects of five added halocarbons (CFC-13, CFC-14, CFC-116, chloroform (CHCl₃) and methylene chloride (CH₂Cl₂)), which are not considered here.

Table 11.2 also gives the overall radiative forcing for halocarbons (feedback case), including the stratospheric-ozone-depletion feedback (negative forcing due to ozone depletion, see Chapter 10). The largest negative effect of the stratospheric-ozone-depletion feedback is found for the Bau90

scenario. Here, the direct radiative forcing for halocarbons of about 1.2 Wm^{-2} over the period 1990-2100 is reduced till 0.4 Wm^{-2} overall forcing, mainly caused by the ongoing ozone depletion for this scenario. However, for the six IPCC-1992 scenarios and the Low-Risk scenario this feedback is positive, enhancing the radiative forcing for halocarbons with 0.05 till 0.15 Wm^{-2} . This is a direct result of the assumed halocarbon emission reductions, which lead to atmospheric chlorine concentrations below the present levels (, thus decreasing the negative ozone forcing due to ozone depletion). These feedback results indicate that an accelerated phase-out of the halocarbons might lead to a minor increase in the overall radiative forcing for halocarbons over the coming century

Figure 11.8: Total radiative forcing for the six IPCC-1992 scenarios and the Low-Risk scenario over the period 1900 to 2100. (trend for IS92f scenario is not shown, to avoid confusion.) Corresponding IPCC-1990 results for 2100 are given on the right (A,B,C and D).

- IS92a scenario
- - - IS92b scenario
- · - IS92c scenario
- · - IS92d scenario
- · - IS92e scenario
- IS92f scenario
- Low Risk scenario

(between 0.1-0.2 Wm^{-2}), and thus has small negative impact on the climate change problem.

Total radiative forcing and CO_2 equivalent concentration Figure 11.8 shows that none of the IPCC-1992 scenarios reaches the low radiative forcing projections of the IPCC-1990 Control Policies and Accelerated Policies scenario. Only the radiative forcing for the Low-Risk scenario forcing stabilizes at a level below that of the IPCC-1990 Accelerated Policies scenario. The same pattern can be seen for the CO_2 -equivalent

concentration (directly coupled to radiative forcing). The CO_2 -equivalent concentrations doubling value (equal to 560 ppmv, based on pre-industrial value of 280 ppmv (Houghton *et al.*, 1990)), is reached around 2025-2035 for all IPCC-1992 scenarios. For the Low-Risk scenario the maximum value of the CO_2 -equivalent concentration is 455 ppmv, reached in 2100.

The overall effect of the feedbacks (feedback case) enhances the radiative forcing with 0.1 till 0.2 Wm^{-2} ($\pm 5\%$) for all IPCC-1992 scenarios and the Low-Risk scenario (all feedbacks are positive for these scena-

Figure 11.9a: Temperature increase for the six IPCC-1992 scenarios and the Low-Risk scenario over the period 1900 to 2100. (shaded area indicates where the absolute temperature target of 2°C is exceeded).

- IS92a scenario
- - - IS92b scenario
- · - IS92c scenario
- · - IS92d scenario
- · - IS92e scenario
- IS92f scenario
- Low Risk scenario

Figure 11.9b: Rate of temperature increase for the six IPCC-1992 scenarios and the Low-Risk scenario over the period 1900 to 2100. (shaded area indicates where the relative temperature target of 0.1 °C per decade is exceeded).

rios). For the BaU90 scenario the negative stratospheric-ozone-depletion feedback largely dominates the methane feedbacks, diminishing the overall forcing with almost 10%. In the further analysis only the base case results are presented.

Temperature changes In Figure 11.9a and 11.9b the simulated absolute and relative global mean temperature values are related to the target level and rate as defined in section 11.4. From these Figures it appears that all IPCC-1992 scenarios exceed the absolute temperature target of 2 °C already

in around 2040 (IS92a,b,e,f), or around 206 (IS92c,d), while the relative temperature target of 0.1 °C per decade is exceeded continuously for almost all scenarios, except IS92c. The dates of achieving the temperature target values for the base case are summarized in Table 11.2. Figure 11.9b also shows that, even for the Low-Risk scenario, it is obviously not possible to stay below the target rate of 0.1 °C per decade during the next two decades. This would imply that, assuming the Low-Risk scenario as a maximum feasible effort towards global sustainable development, there is a commitment to

Figure 11.9c: Six IPCC-1992 scenarios and the Low-Risk scenario related to absolute and relative temperature target levels.

Figure 11.10a: Sea level rise for the six IPCC-1992 scenarios and the Low-Risk scenario over the period 1900 to 2100.

(dark shaded area indicates where the absolute sea level rise target of 0.5 m is exceeded, light shaded area indicates where absolute sea level rise target of 0.2 m is exceeded).

— IS92a scenario
 - - - IS92b scenario
 - - - IS92c scenario
 - - - IS92d scenario
 - - - IS92e scenario
 IS92f scenario
 — Low Risk scenario

future temperature increase which in any case will surpass the target rate till 2010. The information coming from Figures 11.9a and 11.9b is translated into a picture that combines rates and absolute levels of temperature increases (Figure 11.9c). In this Figure the rate of global temperature (per decade) is given as a function of the absolute temperature rise. Identical climate risk areas as in Figure 11.4c are defined, which indicate the potential climate risk with respect to temperature increase. This picture shows that all IPCC-1992 scenario, except IS92c, are associated with high and maximum climate risk

(all scenarios enter the maximum risk area between 2040 and 2070), while the Low-Risk scenario tends to low climate risks (after 2010).

Sea level rise In a similar way as for global temperature rise the global sea-level rise implications for the IPCC-1992 scenarios and the Low-Risk scenario are assessed. Figure 11.10a shows the simulated sea-level rise (base case) compared with the target level interval of 0.2-0.5 m, and Figure 11.10b depicts the simulated sea-level rise per decade compared with the target rate of

Figure 11.10b: Rate of sea level rise for the six IPCC-1992 scenarios and the Low-Risk scenario over the period 1900 to 2100.

(dark shaded area indicates where the relative sea level rise target of 5 cm per decade is exceeded, light shaded area indicates where relative sea level rise target of 2 cm per decade is exceeded).

— IS92a scenario
 - - - IS92b scenario
 - - - IS92c scenario
 - - - IS92d scenario
 - - - IS92e scenario
 IS92f scenario
 — Low Risk scenario

Figure 11.10c: Six IPCC-1992 scenarios and the Low-Risk scenario related to absolute and relative sea level rise target levels.

0.02-0.05 m per decade. These Figures show that the scenarios IS92a,b,e,f exceed the absolute target level in the second half of the next century, and that for the scenarios IS92e,f the rate target level is exceeded from 2020. However, the Low-Risk scenario neither exceeds the target level nor the target rate during the next century, but also the rate of the sea-level rise returns to the target level of 2 cm per decade by 2045 (see also Table 11.2). Apparently the sea-level rise targets as identified by the AGGG (1990c) are weaker than the targets for temperature increase. Analogous to the temperature risk areas five sea-level risk areas are defined which indicate the potential climate risk with respect to sea-level rise: a maximum risk area (>0.5 m and >5 cm/decade), a high risk area (<0.5 m and >5 cm/decade; >0.5 m and 2-5 cm/decade), a moderate risk area (0.2-0.5 m and 2-5 cm/decade; >0.5 m and <2 cm/decade), a low risk area (0.2-0.5 m and <2 cm/decade; <0.2 m and 2-5 cm/decade) and a minimum risk (<0.2 m and <2 cm per decade). Figure 11.10c shows that the IPCC-1992 scenarios might be related to high and maximum risk (after 2060 for the IS92a,b,e,f scenarios), or moderate risks (for the IS92c,d scenarios), whereas the Low-Risk scenario represents a moderate and low risk case (after 2055).

11.5 Delayed Response Strategies

To underscore the importance of the timing of a possible response, an analysis is performed, in which the start of international response actions is delayed from the present to 2000, 2010 and 2020, respectively. It has been assumed that emissions of greenhouse gases would follow the emissions of the IS92a scenario when no action would be taken to limit them. Furthermore, it is assumed that, if the international decision is taken and followed up to start controlling climate change, the policy target would be a scenario that meets the sustainable requirements with respect to the rate and magnitude of the global mean temperature and sea-level rise as defined above: the Low-Risk scenario. Emissions of non-CO₂ gases were assumed to be deflected towards the values associated with the Low-Risk scenario and consequently the allowable emissions of CO₂ were determined. In Figure 11.11 the emissions of CO₂ for the different delayed response runs are depicted.

It appears that waiting until 2000 would imply a necessary decrease of fossil emissions to 70% of 2000-level in 25 years. Ten years later, in 2010, almost 85% emission reduction of 2010-level would have to be achieved in less than 10 years in order to reach the target. Even a slight increase of the emissions is permitted during the second

Figure 11.11: CO₂ emissions from fossil fuel combustion and cement production manufacturing for the delayed response analysis.

half of the next century to reach stabilization, because a continuing decrease of the emissions should result in decreasing concentrations instead of stabilizing concentrations. In consequence of this 'stabilizing concentrations' target, the same temporary increase in emissions occur in the 2020 responses. As can be expected, delaying response until 2020 would render a complete and prompt phase-out of CO₂ emissions from fossil fuel combustion necessary. The resulting changes in atmospheric composition for the delayed response scenarios are represented in Figure 11.12.

This delayed response is a variation on the analysis performed in Rotmans and Swart (1990), which calculated the required fossil emissions reductions when switching from the BaU90 scenario to the target scenario, the IPCC-1990 Control Policies (CP90) scenario.

Schlesinger and Xingjian (1991) made projections of the greenhouse warming until 2100 for the IPCC emissions scenarios. In addition to revising earlier projections, they find that delaying a 20 years transition from the BaU90 scenario to any other scenario has only a small effect on the projected global

Figure 11.12: CO₂ equivalent concentrations for the delayed response analysis.

mean temperature change, regardless of the climate sensitivity. They suggest that the penalty for a 10 year delay is small. From the delayed response analysis of Rotmans and Swart (1990) and from the analysis presented here, however, it follows that delays would severely compromise the world's ability of achieving the target. The conclusions of both studies are apparently contradicting and consequently, confusing for policy makers that have to decide on the urgency of policy measures. The most important reason for this apparent discrepancy is the focus on the interpretation of the results. Rotmans and Swart (1990) show that a 10 year delay in a 20 year transition of the BaU90 scenario to the CP90 scenario from 2000 for instance, may lead to a small temperature penalty, but it would require global carbon dioxide emissions to be reduced by about 20% from 2000 levels or almost 50% from projected levels over this period, with comparable controls of other greenhouse gases. Immediate response would require only a 5% reduction of the global carbon dioxide emissions over the same period to reach the same target. If the final goal of a global climate change policy is to restrain the rate and level of climate change below the target levels as defined above, then the feasibility of the emissions transition becomes increasingly important. Although the eventual temperature effect of a 10 year delay would not be extremely large, it is important to note that the feasibility to realize the necessary transition to control further effects sharply decreases over time. Because of socio-economic and political delays, it will be increasingly difficult to readjust the world's economies and energy systems, and, due to delays in the climate system, it will become more difficult to control the rate and level of climate change.

11.6 Conclusions

Calculations with IMAGE (experimental version 1.6) show that the rate and level of global temperature and sea-level rise resulting from the IPCC-1990 scenarios go far beyond the target levels for temperature

and sea-level as identified by the AGGG (1990c). In terms of climate risk the IPCC-1990 Business-as-Usual (BaU90) scenario as well as the updated IPCC-1992 (IS92a-f) scenarios might be interpreted as maximum risk scenarios. Even the IPCC-1990 Accelerated Policies (AP90) scenario might be considered as a moderate risk scenario for the next fifty years.

The alternative scenario as introduced in this study, called the Low-Risk scenario, shows that the rate and level of global temperature and sea-level rise can be limited to values which are more or less consistent with the AGGG (1990c) targets for temperature and sea-level. According to our model calculations the commitment to future temperature increase implies an exceeding of the target rate of 0.1 °C per decade for the next 20 years. After 2010 the Low-Risk scenario outcomes for temperature and sea-level do not go beyond the defined targets. This indicates that even the AP90 scenario, which might be considered as a maximum effort towards global sustainable development, is associated with a certain risk in terms of exceeding sustainable standards for climate change. Main characteristics of the Low-Risk scenario are a global implementation of CO₂-emission reductions of 20% in 2005 and 50% in 2025 according to the Toronto recommendations (WMO, 1988), a 20% reduction of global methane emissions, a full phase-out of CFCs and maximum control of emissions of nitrous oxide (30% reduction of anthropogenic sources). These emission reductions should result in a stabilization of the CO₂-equivalent concentration at the lowest possible level, in the shortest possible time.

According to our model calculations, the different lag effects in physical and socio-economic processes make a very rapid initiation of international policies necessary in order to limit major risks of climate change. The delayed response analysis in this study shows that the timing of the response of the coming decades is of crucial importance. Although the necessary changes appear to be technically feasible, major social and economic impediments will have to be removed to achieve the recommended reductions. The

al implication of the Low-Risk scenario could be a shift away from fossil fuels, but a complete phase-out would not be necessary. It is a major question whether the global energy system, which is now based for more than 75% on fossil fuel consumption will be capable to cope with the social and economic effects of such a shift.

Worldwide the Low-Risk scenario could only be achieved by a massive and rapid change of the world energy system towards maximum energy efficiency and the application of CO₂-free technology. Although such a change might lead to continuing or even accelerated economic growth for some groups in some countries, there is a risk in major parts of the world that these emissions might only be achieved by limitations to quantitative economic growth which are unacceptable from the viewpoint of the present day national ambitions. The Low-

Risk scenario shows that technologically the world can go a long way towards limiting emissions. Dependent on the economic and technological characteristics and preferences future fuel mixes will vary per country. Increased energy conservation in the broad sense should be the first to implement because of its favourable economic potential and present availability. According to this analysis the emissions of CO₂ in the industrialized countries should be decreased with at least 80% over the coming 50 years in order to prevent serious risks for the world community. Delays in policy formulation will be followed by long lead times for introduction of measures increasing the amount of climate change 'in the bank' because of the slow response of the physical climate system. Therefore rapid response is warranted.

2 The impact of a sea level rise on the Dutch coastal defence system

Chapter is based on: Elzen, M.G.J. den, and Rotmans, J. (1992b): *The Socio-Economic Impact of Sea Level Rise on The Netherlands: A Study of Possible Scenarios. Climatic Change, Vol 20, no. 3, 169-195.*

1 Introduction

Undoubtedly sea-level rise is potentially one of the most threatening consequences of the greenhouse phenomenon. Nearly one-third of the world's population, including many of the largest cities, lives within 60 km of a coastline. A sea-level rise, even of less than one meter, would have a tremendous influence on habitation patterns, causing large-scale migrations of millions of people. Because of the vulnerability of the Netherlands to rises in sea-level, which resulted in the so-called delta flood protection plan after the last major flood in 1953, sea-level rise is a very important topic in this country.

As described in the previous Chapter, even with substantial decreases in the emissions of the major greenhouse gases, future increases in temperature, and consequently, sea level rise are unavoidable due to lags in the climate system. There are four major climate-related processes that induce this future sea level rise: thermal expansion of ocean water, melting of mountain glaciers and small ice caps, and the reaction of the Greenland ice sheet and the Antarctic ice sheet (Warrick and Oerlemans, 1990). During the last century the sea-level rise has been about 10-20 cm, which can be explained by these processes, except the presently unknown reaction of the Antarctic ice sheet. The variation in this estimate have their origin in local effects. For the Netherlands and Belgium the rise in the sea-level off the coast line during the last century lay in the upper bound of this range, being about 20 cm.

In order to assess the socio-economic impact of a sea-level rise for the

Netherlands, IMAGE (experimental version 1.6) contains a separate socio-economic impact model, in which the costs of coastal defence and water management for the Netherlands are calculated as a result of adaption to the impacts of sea-level rise. This model is described in detail in den Elzen and Rotmans (1992b; 1988; 1989), and briefly described here. In this Chapter the model is used for calculating the future changes in safety level (frequency of overflowing) as a result of sea level rise and possible future dike raising strategies. Next, a risk based cost minimization approach is presented for calculating the optimal economic safety level, and the related optimal dike raising.

12.2 General Model description

The socio-economic impact model represents a simplification of the complicated mechanisms in the fields of coastal defence and water management, and is described by dynamic relationships between input (climate change, sea-level rise) and output (damage or profit, expressed in terms of money) (den Elzen and Rotmans, 1992b). The simulation period of the impact model is 110 years, from 1990 to 2100, in contrast to the simulation period of 200 years for the global phenomena. The socio-economic impact model consists of independent, interlinked impact modules, which are based on both an extensive study of the literature and knowledge transferred as a result of a close cooperation with expert Dutch specialists from Rijkswaterstaat Netherlands and Delft Hydraulics. These two institutes have completed a comprehensive and

Figure 12.1: System diagram of the socio-economic impact model (den Elzen and Rotmans, 1992b)

global assessment
 regional assessment

detailed study of the Impact of Sea Level Rise On Society (ISOS). By contrast, our socio-economic impact modules are but the end of the climate change cause-effect relationship, and try rather to give rough estimates, in terms of indicative figures, of what global scenarios might imply for the Netherlands. The structure of the socio-economic model is shown in Figure 12.1. This Figure shows that the model is mainly concentrating on two sectors of the Dutch society: the coastal defence and the water management.

Coastal Defence modules

The Netherlands have been struggling with the sea level for hundreds of years, the result being a highly organized protection system of dikes and dunes. Figures 12.2 maps the coastal defence system of the country. Three kinds of coastal defence systems are considered: dikes, dunes and intertidal zones. The dikes are segmented into three parts: the Delta area, the Western and the Northern part. The dunes are mainly concentrated in the Western part and the Frisian Islands. The main intertidal areas in the Netherlands are

the Wadden area and the Delta area. A sea level rise induced by climate change would affect the structure of this protection system. Because it is not yet possible to quantify the ecological and geomorphological impacts, the socio-economic impact model only considers the economic and societal implications of sea level rise for the Netherlands. The economic impacts relate to the protection of coastal area by dike raising and dune strengthening. Several mathematical models have been developed in order to study the effects of dike raising on the safety level. One model considers dike raising as an economic decision problem and calculates based on a risk-based cost minimization approach, which takes into account of the safety levels, dike raising costs and the expected costs of damage in case of an inundation, the optimum dike raising, and the related optimum safety level. Another model focuses primarily on stabilizing the present 1990 safety level. In regard to the protection of the sandy coast the socio-economic impact model depends heavily upon more detailed models developed and used by Dutch Rijkswaterstaat.

The losses of intertidal areas has been calculated in the model in a very schematic way, in consideration of the barely known

changes in the morphology of intertidal zones, these morphological changes are largely determined by a change of the tidal volume in relation to a change of the cross-section of the tidal inlet (de Ronde, 1988). Another difficulty is related to the fact that it is hardly possible to express loss of intertidal area in terms of money. Therefore the economic consequences of losses of intertidal zones are neglected in the model.

Water management modules

With regard to the water management sector various areas have been differentiated: 22 seepage areas, 7 drainage areas, the New Waterway area (for salt intrusion), and the IJssel lake. Based on this zoning both the principal financial consequences and the various alternative countermeasures for the water management sector are calculated by the water management modules in parallel. Besides the purely economic aspects, the socio-economic impacts of sea-level rise have been treated in this sector, such as salt intrusion in the New Waterway, seepage and drainage problems in the low-situated areas behind the dunes, drainage, and the maintenance of the IJssel Lake. One of the missing links in our socio-economic modules

Figure 12.2 : Coastal defense system of the Netherlands

is the regional shift in the main hydrological pattern, which directly influences the runoff of the great rivers Rhine and Meuse and thus the water balance of the whole country.

12.3 Risk analysis of the coastal defence system: dikes

The Dutch coastline is half protected by dikes (see *Figure 12.2*). Two types of dikes may be distinguished, those subject to wave-attack and those without wave-attack. These two types of dike differ in their average height. Dikes with wave-attack have a height of 10-15 m N.A.L. (Normal Amsterdam Level), whereas those without wave-attack are lower, from 5-7 m N.A.L. This difference is related to the situation of the dikes. Dikes with wave-attack are sited along the Dutch coast in direct contact with the open North Sea, and must be able to resist a storm surge of +5 m N.A.L. and its attendant heavy wave attacks. These heavy wave attacks necessitate an extra dike height of 5-10 m, on top of the +5 m N.A.L. required for the storm surges, resulting in a total dike height of 10-15 m N.A.L. By contrast, those dikes which are not subject to wave attack are situated in Zeeland and along the Northern coast, and they have no direct contact with the North Sea (*Figure 12.2*). For these dikes a dike height of 5-7 m is sufficient.

On the assumption that the Dutch coastal defence system will only be extended and reinforced, but not fundamentally altered, an attempt has been made to model the consequences for these two kinds of coastal defence systems of an accelerated sea-level rise. When raising the dikes, two additional features should be taken into account.

1. The additional sea-level rise of 5 cm due to the high tide level. As a consequence of this, the maintenance of the present 1990 safety level implies an additional dike raising of 0.05 m (Eversdijk, 1989).

2. The extra strength of the higher waves requires an extra increase in the height of the dikes subject to wave attack, which is represented by a correction factor.

Safety

Safety is defined here as the protection against inundation, which can be expressed in terms of the frequency with which the flood protection system is overtopped. After the disastrous flood on February 1953 in Zeeland, as a result of which most of the Delta area in the Netherlands was inundated, almost all dikes along the Dutch coast were raised to a height which now enables them to resist a storm surge of +5 m N.A.L. The presently assigned theoretical chance of inundation, the so-called 'Delta norm', is 0.0001 for Central Holland, being a risk of inundation once every 10,000 years, and 0.00025 for the other threatened areas in the Netherlands: Zeeland and the Northern part. The last big storm of 1953 reached +3.8 m N.A.L. and had a statistical chance of inundation of 0.0045 (Delta Commission, 1960). The relationship between frequency of overtopping and sea-level rise is assumed to be exponential, based on historical sea level data (van Dantzig, 1956; de Jong, 1985; Rijkswaterstaat, 1989; de Ronde, 1982; Deltacommission, 1960; Vrijling, 1985).

$$p(h \geq H)_i(t) = p(h \geq H)_{i,ic} \exp[\ln(10)\alpha \Delta H_i(t)] \quad (12.1)$$

where $p(h \geq H)_i(t)$ denotes the probability that dike height H will be exceeded at time t in area i , $i=1,2,3$, H the height of dike above mean sea level (0 m N.A.L.) (m), α the gradient of flooding frequencies of storm surges ($= 1.5$, Wind (1987)), $p(h \geq H)_{i,ic}$ the safety norm in 1990 area i (equal to 0.0001 for area 1, and 0.00025 for area 2 and 3, *Table 12.1*), $\Delta H_i(t) = \Delta S_{tot}(t) + \phi + CR(t) - DR_i(t)$, $\Delta S_{tot}(t)$ the sea-level rise at time t (m), ϕ equal to 0.05, as a consequence of an extra rise of 0.05 m for the high tide, when sea-level rises (m), $CR(t)$ correction factor for dike raising, caused by extra wave height in case of dikes subject to with wave attack (m) ($= \mu \Delta S_{tot}(t)$), μ equal to 0.6, for dikes subject to wave attack (de Ronde and de Vogel, 1989), and 0.0, for dikes without wave attack, and $DR_i(t)$ the total dike height

increase at time t for area i (m).

In practice this means that reducing the present safety norm (equivalently, the Delta Norm) of 0.0001 to 0.1 requires a dike raising of about 0.70 m.

Dike raising

An accelerating sea-level rise will cause a decrease in safety, according to Equation (12.1), which means that numbers of people and quantities of goods will be at risk. Countering this threat requires a raising of the dikes. Because it seems impossible to predict both the amount of sea-level rise and the rate at which it will rise, the dike raising is assumed to be carried out in a stepwise manner. Construction in one step would carry with it an unnecessarily high financial and material risk. Based on this assumption, the total dike raising for the whole period 1990-2100 is calculated. Subsequently an algorithm is applied which generates the time pathway of a stepwise dike raising for the whole period to 2100, using the previously calculated total dike raising. This algorithm is described in detail in den Elzen and Rotmans (1988).

As mentioned above the total height to which a dike should be raised depends upon the type of dike under consideration. Besides adaptation to sea-level rise itself, additional standard increments are necessary due to both the high tide level and to an increase in the height of the waves. The latter need only be considered for dikes subject to wave attack, of course.

Two different strategies for raising the heights of the dikes are distinguished. The first strategy considers the problem of dike raising as an economic decision problem, where the criterion for dike raising is related to the value of the people and materials at risk. This implies that the present safety norm will can no longer be fixed in advance at 0.0001, but should be calculated on the basis of this risk-based cost minimization approach (optimum safety level). Now the optimum dike raising strategy is calculated, involving the determination of the minimum costs of raising the dikes for the period 1990-2100. This results in the following total dike

raising:

$$DR_i(2100) = OPDR_i + \phi + CR(2100) \quad (12.2)$$

where $DR_i(2100)$ is the total dike raising in the year 2100 in area i , $i=1,2,3$ (m), and $OPDR_i$ the optimum dike raising in area i (m).

The object function to be minimized in this analysis is the total risk-based costs over the period 1990-2100. These risk-based costs comprise the costs of dike raising, and the capitalized damage expectation of the material and human losses should dike breach occur. It should be noted that the costs have been expressed in terms of constant (1990) Dutch guilders (Dfl: 1 Dfl is approximately 0.5 US Dollar). This object function is expressed in Equation (12.3) (den Elzen and Rotmans, 1988; 1992b). The costs of dike raising are supposed increase linearly with the height of the dike; this means that if the dike is raised by x m, the costs of dike raising will be proportional to the product of the marginal costs of dike raising per m raised per km dike, and the factor x . To carry out this economic analysis in a sound way, all economic monetary units (in Dfl) in our object function (Equation 12.3) have to be discounted to the year 1990.

$$I_i [I_i + k_i ODPR_i] + \sum_{t=1990}^{2100} (1 - \delta/100)^{t-1990} W_i p(h \geq H)_{i,c} \exp [\alpha \ln(10) (\Delta S_{tot}(t) - ODPR_i)] \quad (12.3)$$

where I_i is the initial costs of dike raising for 1 km dike, $i=1,2,3$ (Dfl/km), l_i the length of dikes in area i (km), k_i the marginal costs of dike raising in area i per m increase in height per km dike (Dfl/m.km), δ the reduced rate of interest (real interest minus inflation) (%), W_i the economic value of area i at risk in 1990 (Dfl) ($= p_d N_i V + M_i$), M_i the capitalized value of the protected goods, including firms, cattle, etc. for area i (Dfl), p_d the probability of dying given an inundation (Table 12.1, Vrijling, 1985), N_i the number of people protected in area i , and V the capitalized value of one human being

Table 12.1: The values of the parameters used in the socio-economic model. The economic values are based on projections of the Central Planning Bureau (CPB, 1984)

	area 1 Central Holland	area 2 Zeeland (+inner Zeeland)	area 3 Friesland and Groningen
gradient of frequencies (α)	1.5	1.5	1.5
present safety norm $p(h \geq H)_{i,ic}$	0.0001	0.00025	0.00025
Initial costs of dike raising (I_i) (Dfl/m)	3 10 ⁶	3 10 ⁶	3 10 ⁶
marginal costs of dike raising (k_i) (Dfl/m.km)	4 10 ⁶	4 10 ⁶	4 10 ⁶
reduced rate of interest (δ)	2	2	2
economic value of materials at risk (M_i) (Dfl)	1.418 10 ¹²	2.67 10 ¹¹	2.85 10 ¹¹
chance of dying at inundation (p_d)	0.01	0.01	0.01
capitalized value of a human being (Dfl) (V)	5 10 ⁶	5 10 ⁶	5 10 ⁶
number of people (in 1985) (N_i)	6.05 10 ⁶	0.85 10 ⁶	1.3 10 ⁶
length of dikes (l_i) (km)			
with wave attack	45	90	15
without wave attack		(370)	150

in 1990 (Table 12.1) (Dfl).

This reaches a minimum for the optimum increase in the height of the dike: The optimal safety level for each region can now be calculated combining Equations (12.1), (12.2) and (12.4). The values of all parameters used are listed in Table 12.1. The

$$\begin{aligned}
 ODPR_i = & \ln [\ln(10)\alpha W_i p(h \geq H)_{i,ic} \\
 & \sum_{t=1990}^{2100} (1-\delta/100)^{t-1990} \exp [\ln(10)\alpha \Delta S_{tot}(t)]/k_i l_i] / [\ln(10)\alpha] \quad (12.4)
 \end{aligned}$$

inner dikes in Zeeland, which are excluded from the economic analysis, are in fact considered in the calculation of the total dike raising costs. For such dikes the amount by which they have to be raised is equal to the total increase in height for dikes without

wave-attack in Zeeland as a whole.

The second strategy is based on maintaining the present safety norm. Actually this implies that an increase in the height of a dike will approximately follow the rise in sea-level. In order to realize a constant safety level, the total increase in dike height is determined by using a modified version of Equation (12.2). The optimum dike raising factor for area i ($= OPDR_i$) is now replaced by the sea-level rise over the period 1990-2100 ($= \Delta S_{tot}(2100)$).

12.4 Results

All model calculations presented in this section are based upon the IPCC-1990 emission scenarios. In the Figures only the range built up from the IPCC-1990 Business-as-Usual (BaU90) and Accelerated Policies

Figure 12.3 : Flooding frequency (safety) of the threatened area in the present situation and in case of sea level rise of 0.5 m and 1 m

(AP90) scenarios are presented. The simulation period is 110 years, from 1990 till 2100, depicted on the horizontal axis in the Figures, while the simulated variable is represented on the vertical axis.

Coastal defence

The frequencies with which the flood

protection for a threatened area is overtopped in the present situation, as well as in a situation with a sea-level rise of 0.5 m and 1.0 m are given in Figure 12.3. The frequency of overtopping increases up to about 0.0008 for the AP90 scenario and about 0.003 for BaU90 scenario for Central Holland in 2100; the latter value tends to the statistical chance of inundation of the

Figure 12.4: Flooding frequency (safety) for the IPCC-1990 Business-as-Usual and Accelerated Policies scenario (no dike rising)

disastrous big storm surge in 1953 (Figure 12.4).

Figure 12.5 shows how the safety of the Western coastal zone (Central Holland) will change using a risk-based cost minimization approach for calculating the optimum dike raising and safety levels for the two IPCC-1990 scenarios. The frequency graph is sawtoothed as a result of the sudden drop after each increase in dike height. After this point, the frequency will slowly increase under the influence of a continuing rise in sea-level. The frequency at the end of the

simulation ranges from 0.0000016 (AP90 scenario) to 0.0000028 (BaU90 scenario), being on average of 0.0000022, or a fortieth of the present Delta Norm of 0.0001 in Central Holland. For Zeeland the final average frequency is about 0.000025 (a tenth of the Deltanorm of 0.00025 for Zeeland), and for Friesland and Groningen the final average frequency is about 0.00003 (a eighth of the Deltanorm of 0.00025 for that area). Because the 'average' frequency forms the result of an economic analysis, which takes account of the future worth of material goods

Figure 12.5: Flooding frequency (safety) for the IPCC-1990 Business-as-Usual and Accelerated Policies scenario (the risk-based cost approach for calculating the optimum dike rising safety level).

Figure 12.6: Step-wise dike raising for the IPCC-1990 Business-as-Usual and Accelerated Policies scenario (the risk-based cost approach for calculating the optimum dike raising safety level).

— IPCC-1990 Business-as-Usual scenario
 - - - IPCC-1990 Accelerated Policies scenario

and people at risk, this value can be considered as a new safety level (the optimum safety level). However, this value is much lower than the present safety level, or Delta Norm. This means that, at the end of the next century, after having simulated several dike raising steps, the increased economic worth of the threatened area necessitates a stricter safety norm. Based on this frequency it can be concluded that the Delta Norm should be made more strict. Figure 12.6 presents the calculated stepwise raising of the height of the dikes over the period 1990-2100 for the Western zone (Central Holland) for the BaU90 and AP90 scenario under an optimum dike raising strategy. The number of steps and the increment in height per step depend on the total dike raising and the minimum height by which a dike can be raised, which has been chosen as 30 cm. The optimum dike raising for the period 1990-2100 for the BaU90 scenario is about 1.7 m (Central Holland), 1.3 m (Zeeland) and 1.15 m (Friesland and Groningen). As can be seen in the Figure the total dike raising for Central Holland is due to the correction factor for dikes subject to wave-attack, somewhat higher, 2.1 m. The total involved dike raising costs of about 21 billion guilders. For the AP90 scenario the optimal dike raising in 2100 is about 1.60 m (Central Holland), 1.20 m (Zeeland) and 1.05 m (Friesland and Groningen), and the total

costs amount to about 20 billion guilders.

For the second strategy, maintaining the present safety norm, the range for the total costs varies from about 15 to 18 billion guilders. Besides the economic decision strategy a second strategy is used to calculate the stepwise dike raising. This strategy is primarily based on the principle that the present safety norm should be maintained. The results for the second strategy are depicted in Figure 12.7, which shows the calculated dike raising for the Western zone for the period 1990-2100. The simulated total dike raising in the year 2100 varies from about 0.6 to 1.00 m.

Sensitivity Analysis

In order to show the reaction of our model to abrupt changes in the sea-level rise, a kind of a sensitivity analysis is performed. A hypothetical, discontinuous sea-level rise is introduced, which is shown in Figure 12.8.

The resulting flooding frequencies are depicted for both strategies in Figure 12.9, where strategy 1 represents the optimal dike raising method, and strategy 2 shows the economic analysis. In this Figure strategy 1 represents the economic decision method which calculates the optimal dike raising, while strategy 2 calculates the dike raising, under the supposition that the present safety norm will be maintained. Figure 12.9 shows

Figure 12.7: Step-wise dike raising for the IPCC-1990 Business-as-Usual and Accelerated Policies scenario (strategy 2).

— IPCC-1990 Business-as-Usual scenario
 - - - IPCC-1990 Accelerated Policies scenario

that, during the first part of the simulation, the flooding frequencies decrease rapidly in both cases. This is due to a number of increases in dike height, as an immediate response of the model to an accelerated (abrupt) sea-level rise. After 2010 the frequency of strategy 2 aims at the present safety level of 0.0001, whereas the economic optimum frequency of strategy 1 is much lower.

12.5 Conclusions

Simulations with the socio-economic impact model suggest that the frequency of inundation will increase with a factor eight till thirty compared to the Delta Norm (the present safety level of 0.0001) for the IPCC-1990 scenarios. The upper limit tends to the statistical chance of inundation of the

disastrous big storm surge in 1953.

To counteract these increased risks for an inundation the dikes should be raised already before 2000, otherwise the safety of the population will decrease far below the Delta Norm. Applying the risk-based cost minimization approach for calculating the optimum dike raising strategy and safety level, which is to be preferred from an economic point of view, it follows that the minimal extra dike raising for the next century is about 2 m for Central Holland, 1.5 m for Zeeland, and 1 m for Friesland and Groningen. This would imply high costs, amounting to about 20 billion guilders. A major inference is that the Delta Norm is too low and should be tightened up to a eighth till a fortieth of the present value (the optimum safety level), entailing a better protection of human lives and material goods.

13 The impact of ozone depletion on human health: the incidence of skin cancer in the Netherlands

13.1 Introduction

Excessive levels of UV radiation are likely to imply a multitude of harmful effects on human health and the environment. The adverse effects on human health are: sunburn, skin cancer, skin ageing, cataracts, and a probable impairment of human resistance to infectious diseases. The effects of excessive levels of UV on agriculture and ecosystems are: reduced crop yields, damage to phytoplankton, and adverse effects on aquatic food chains. In addition, excessive UV levels have an, albeit indirect, negative effect on the climate change problem, since a reduction of oceanic biological productivity (resulting from UV damage suffered by phytoplankton), curtails oceanic uptake of atmospheric CO₂ (UNEP, 1989; UNEP, 1991c).

Most of these effects are caused by the UV-B component of UV radiation, i.e. the wavelengths between 280 and 320 nm, which is the most biologically effective type of UV radiation, because of its high energy intensity, and the fact that it is only partially absorbed (or scattered) in the atmosphere. Such absorption is mainly by stratospheric ozone, and to a lesser extent clouds, tropospheric ozone and aerosols (hereafter collectively referred to as the other UV-B filtering factors). If the other UV-B filtering factors remain constant, ozone depletion will therefore result in an increase in UV-B radiation reaching the Earth's surface, and further enhance UV-B related negative impacts. However, in some industrialized regions, ground-station measurements show a negative UV-B radiation trend (UNEP, 1989; Madronich *et al.*, 1991), a trend which belies the observed trend towards depletion of stratospheric ozone over the last decade

(Stolarski *et al.*, 1991). The explanation of this paradox is probably found in the increases in tropospheric ozone levels and atmospheric quantities of aerosols associated with air pollution, factors which clearly underline the importance, as well as the debatable role of, the other UV-B filtering factors.

This Chapter focuses a single impact on human health, namely: the proliferation of skin cancer, not only because this is a matter of current public concern, but also because it yields useful data. Skin cancer incidence in the middle and high latitudes is expected to increase as a result of increases in UV-B radiation penetrating the atmosphere associated with stratospheric ozone depletion (assuming that the other UV-B limiting factors remain constant). This study focuses on the changes in future incidence levels of skin cancer in the Netherlands due to increased UV-B radiation levels associated with stratospheric ozone depletion in the Netherlands (with a current annual total of 15 to 18 thousand cases). The analysis was conducted using the UV-B chain model (the coupled halocarbon/UV-B impact model, which was first described in Slaper *et al.*, 1992), which is part of IMAGE (experimental version 1.6). This model describes the cause-effect relationships underlying the ozone depletion problem: consumption policies vis-à-vis chlorofluorocarbons (CFCs) and other halocarbons, global stratospheric chlorine concentrations, local depletions of stratospheric ozone, the resulting increases in UV-B levels, and finally the resulting effects on human health effects, in terms of skin cancer risks.

Previous studies have mainly focused on specific elements in this cause-effect chain, i.e. the increases in effective UV-B irradi-

ance related to depletion of stratospheric ozone (Kelfkens *et al.*, 1990, Madronich *et al.*, 1991), or the UV-B dose response relationship associated with skin cancer incidence (Scotto *et al.*, 1981; Gruijl *et al.*, 1980; Gruijl, 1982; Rundel, 1983; Slaper *et al.*, 1986; Moan, 1991; Longstreth *et al.*, 1991). Hitherto, the only rough estimates of extra skin cancer incidences due to ozone depletion presented by UNEP (1989) and UNEP (1991c) have been approximate and provisional.

This Chapter is structured as follows: section 13.2 provides a short overview of the scientific background of ozone depletion and its environmental and human health impacts. Section 13.3 presents the UV-B impact model, which is part of the UV chain model. Section 13.4 presents projections of mortality rates due to stratospheric ozone depletion for the Netherlands based on model simulation experiments with the UV-B chain model for a number of halocarbon policies (including the Copenhagen Amendments), and evaluates these results with respect to the public health risk targets, which are based on health risk targets for ionized radiation, as formulated by VROM (1992). Finally, conclusions arising from these experiments are drawn in section 13.5.

13.2 Scientific background

13.2.1 Observations of ozone depletion

Since October 1978, the Total Ozone Mapping Spectrometer (TOMS) on the Nimbus 7 satellite has been measuring the total thickness of the ozone layer, and is still taking about 190,000 daily measurements. Stolarski *et al.* (1991) have analysed the data pertaining to the period from November 1978 up to May 1989, and have developed a statistical model, incorporating mathematical expressions of seasonal variation, linear trend, solar activity cycle, quasi-biennial oscillation, and second-order autoregressive noise, as relevant to the ozone data. The linear trend that Stolarski *et al.* (1991) found between the latitudes 65°S and 65°N over the last decade was proceeding at an annual rate of approximately $0.26 \pm 0.14\%$. Figure 13.1 depicts the ozone trend over the last decade as a function of the latitude and season as described by Stolarski *et al.* (1991). In the tropical zones (latitudes between 30°S to 30°N) no significant ozone depletion was found. In the Northern Hemisphere, stratospheric ozone depletion at the middle latitude 50°N (the Netherlands is situated at 52°N) is proceeding at an annual rate of approximately $0.5 \pm 0.2\%$ with an annually-averaged seasonal variation of 0.8% in February and March, and 0.2% in July and

Figure 13.1: Ozone trend (%/year) obtained from TOMS total ozone data as a function of latitude and season. Data included extends from november 1978 through March 1991 (WMO, 1992)

Indicates area where trends are statistically significant at the 2 σ level

August. Between 30°N till 50°N (latitudinal belt of the United States) the annual negative trend is approximately 0.3 to 0.5%. The data indicate a maximum annual negative stratospheric ozone trend of approximately $0.9 \pm 0.3\%$, which is centred at 45°N in February and March. In the Southern Hemisphere, an annual negative ozone trend of 0.4% or more was found at all latitudes south of 40°S throughout the year.

Recent data, based on both satellite and ground-station measurements, indicate that previous trends have continued (Stolarski *et al.*, 1992). In late 1991, after the Mt. Pinatubo eruption, the equatorial ozone measured by TOMS had decreased by 4-5%, which was consistent with the model calculations. Unprecedented low ozone levels were observed in 1992 and early 1993, at several bands of latitudes in both hemispheres, but not in the equatorial region, an anomaly which could well be explained by the Mt. Pinatubo eruption (Gleason *et al.*, 1993).

Observations above Antarctica recorded during the last six years demonstrate that in the Antarctic spring seasons of 1987, 1989, 1990, 1991, and 1992, the ozone column was reduced by more than 50%, and more than 95% of the ozone concentrations found at altitudes between 15 and 20 km had been destroyed (WMO, 1992; 1992a).

Recent laboratory research and reinterpretation of field measurements have lent support to the scientific evidence that chlorinated and brominated chemicals are primarily responsible for the Antarctic ozone hole, as well as for the observed ozone losses at middle and high latitudes (WMO, 1992; WMO, 1992a).

13.2.2 Consequences of ozone depletion vis-à-vis UV-B radiation

There is no scientific doubt that ozone depletion, as described above, leads to an increase in UV-B radiation reaching the Earth's surface (if all other UV-B influencing factors (clouds, tropospheric ozone and aerosols) remain constant). This view is confirmed by observations over the Antarctic at times when the ozone hole was present, since significant increases in UV-B radiation were

then observed (Stamnes *et al.*, 1990; Lubin *et al.*, 1991; Madronich *et al.*, 1991) which, under clear-sky conditions, were consistent with theoretical predictions (WMO, 1992). The same holds for observations recorded above Melbourne (Australia) in December 1987 (Roy *et al.*, 1990).

However, the other UV-B influencing factors also, play a role in the ultimate penetration of UV-B radiation to the Earth's surface. Paradoxically, the measurements of UV-B radiation reaching the Earth's surface which are currently available (Cotton, 1990), show negative trends over the past decade in some industrialized regions in the middle latitudes of the Northern Hemisphere (UNEP, 1989; Madronich *et al.*, 1991), despite the observed stratospheric ozone losses. An example is the observed annual negative UV radiation trend of between 0.5% and 1.1% reaching ground-level as observed by the 25 UV-B measurements stations in the United States (Scotto *et al.*, 1988). Increases in tropospheric ozone (Bruhl and Crutzen, 1989) and aerosols associated with air pollution (Seckmeyer and McKenzie, 1992) may be the probable explanation for such negative UV-B trends, since UV-B measurements were primarily taken in the vicinity of urban and semi-rural areas (Madronich *et al.*, 1991).

In future, the importance of tropospheric ozone and aerosols is likely to be diminished if (inter)national policies directed at reducing air pollution are effective. Moreover, the significance of cloud formations is likely to be influenced by climate change. However, in view of considerable uncertainties about how cloud distributions and optical filtering properties will change as a result of climate change, no reliable prognoses about the magnitude of the effects of clouds on UV-B radiation can be provided, and there is no certainty about whether heavy cloud formations would increase or decrease the levels of UV-B radiation reaching the Earth's surface.

In view of the many uncertainties inherent in the factors: clouds, aerosols and tropospheric ozone replenishment, this study cannot consider their influence on UV-B radiation. We therefore intend to concentrate on the possible increases in levels of UV-B reaching the Earth's surface which can be associated with ozone depletion.

13.2.3 Environmental effects of ozone depletion

The effects of additional UV-B radiation on the environment have not yet been rigorously studied, but most researchers believe them to be adverse, directly or indirectly, with respect to life on Earth. Relatively minor increases in UV-B radiation are expected to affect plants, reducing growth and crop yields, and thus implying serious consequences for the world food supply. Increased levels of UV-B radiation are also expected to have an adverse effect on the primary production of marine phytoplankton, a decline in which would diminish the zooplankton, which is a basic food for fish. Such a decrease in phytoplankton could also considerably limit the oceans' ability to act as a sink for carbon dioxide, and if this capacity decreases, the atmospheric carbon dioxide concentration will increase, and further enhance global warming. Other possible impacts of increases in UV-B radiation are negative effects on tropospheric air quality, animal health and materials.

Quantitative understanding of many of these effects, e.g. effects on plants and micro-organisms, is far from complete, and this question is not considered here.

13.2.4 Effects of ozone depletion on human health i.e. incidence of skin cancer

The direct effects of increasing UV-B levels on human health include: the suppression of the body's immune system that might lead to increases in the occurrence or severity of infectious diseases, increased damage to the eyes, especially in the form of cataracts, and increases in the immediate effects on the human skin (such as sunburn and pigmentation), as well as increases in the longer-term changes (after a number of years or decades), such as skin ageing, and skin cancer incidence, in particular among the fair-skinned population (UNEP, 1991c).

This study focuses on the changes in the incidence of skin cancer associated with stratospheric ozone depletion. Two types of skin cancer should be distinguished: non-melanoma skin cancer and melanoma skin

cancer. The most common type is the non-melanoma skin cancer (about 90% of cases), with a mortality rate which is usually less than 1%. Non-melanoma skin cancer is subdivided into basal cell carcinoma (BCC) and squamous cell carcinoma (SCC). UV-exposure is generally considered to be the major cause of the occurrence of non-melanoma skin cancers (UNEP, 1989). The other type of skin cancer, melanoma skin cancer (MSC), is less common, but is associated with a much higher rate of fatalities (about 25%). The relationship between UV-exposure and melanoma incidence is not clear, and while experts now believe that UV-radiation might be an important contributory factor in the genesis of melanomas, the exact nature of its contribution is still not well-known.

The causal role of UV-exposure in the incidence skin cancer is illustrated by the data collated by Slaper *et al.* (1992):

- the incidences of both non-melanoma and melanoma skin cancers are greater at lower geographical latitudes, where solar UV-irradiance is more intense;
- incidence of non-melanoma skin cancer is higher among people with outdoor professions (this does not apply to melanoma skin cancer);
- melanoma skin cancers occur primarily on the most exposed skin sites (approximately 80% occur on head and hands). In the case of melanoma skin cancer this percentage is 20-25%.
- non-melanoma and melanoma incidences are higher among fair-skinned people, and especially those susceptible to sunburn.
- incidences are higher among people who suffer from genetic disorders associated with increased sensitivity to the sun.
- UV-radiation induces skin cancer in animals (extensive dose-response studies have shown clear relationships between UV exposure and the induction of squamous cell carcinoma in mice and rats.
- UV radiation induces damage and mutations in cellular DNA and can cause cell death.

Present incidence and mortality rates for two countries:

The Netherlands

The present incidence of non-melanoma skin cancer is not very well-known in the Netherlands due to an incomplete registration (Slaper *et al.*, 1992). Based on an extrapolation of the incidence figures of the United States presented by the third National skin cancer survey (Scotto *et al.*, 1981), and taking into account the lower solar intensity in the Netherlands, the non-melanoma skin cancer incidence is estimated at 18,750 cases per year (1250 per million). Neering and Cramer (1988) estimated the incidence at 15,000 cases yearly (1000 per million). Following Slaper *et al.* (1992), this study assumes the incidence to be 16,500 cases per year: whereby the annual incidence of basal cell carcinomas is 15,000 cases (1000 per million) and that of squamous cell carcinoma 1500 cases (100 per million).

The risk of mortality is estimated at 0.3% for basal cell carcinoma, and 3% for squamous cell carcinoma. These fractions are in accordance with the present annual mortality rate for non-melanoma skin cancer in the Netherlands which is 80-90 cases (6 per million), and a more reliable statistic.

Over recent decades, the incidence of melanoma skin cancer has increased rapidly in the Netherlands. That these increases are much greater than expected is due to the changes in the size and age distribution of the population, and to ozone depletion. It is presently believed that 'sunworshipping' holidays are a major factor explaining the rising melanoma incidence, although, the evidence supporting this view is not conclusive (UNEP, 1991c; UNEP, 1989). The observed mortality rate has increased almost sevenfold, from 3 per million in 1950 to 20 per million in 1990 (an annual increase of 5-7%). The present rate of 20 per million represents 300 cases per year, and in view of the present incidence of about 1200 cases (80 per million) reported by Neelemans and Rampen (1990), the risk of mortality is estimated at 25%.

the United States

The observed incidence of non-melanoma skin cancer in the United States in 1977 was about 500,000 cases per year (2320 per million), whereby a basal cell carcinoma (BCC) and squamous cell carcinoma stood in a ratio of 4:1 (Scotto *et al.*, 1981; Longstreth *et al.*, 1991). The present observed melanoma skin cancer incidence in the United States is equal to 90 per million (Scotto *et al.*, 1991). New information from the northwestern United States as described in Longstreth *et al.* (1991) reports an incidence rate of squamous cell carcinoma (SCC) of 1060 per million in 1986. A 4:1 ratio between BCC and SCC as observed in earlier studies would imply a non-melanoma skin cancer incidence rate of 5000 per million (more than one million cases per year). This rate is much higher than the rate of 2320 per million (500,000 cases per year) reported by Scotto *et al.* (1981). The risk of mortality for the three skin cancer types (SCC, BCC and melanoma skin cancer) are assumed to be equal to the assumed risks for the Dutch situation, namely: 0.3% for basal cell carcinoma, and 3% for squamous cell carcinoma and 25% for melanoma skin cancer.

13.3 Methodology

13.3.1 Introduction

The tool used in this study is the UV-B chain model, a policy-oriented model, which links the scientific evidence with policies for controlling stratospheric ozone depletion. More specifically, this integrated model considers the entire cause-effect chain, from the production of halocarbons in industry, the emission thereof from households and landfill sites, the dispersion of the released chlorine atoms in the stratosphere, to the increased UV-B exposure at the Earth's surface, and finally the adverse human health effects, in terms of skin cancer risks due to ozone depletion for two countries (the Netherlands and the United States) (Slaper *et al.*, 1992). In order to model this cause-effect chain, the model incorporates data gleaned from various scientific disciplines, i.e. atmospheric

chemistry, atmospheric optics, and UV-dose effect biology.

The model can be used to give policy makers and specialists a clear and concise overview of the cause-effect mechanisms associated with the ozone problem, i.e. the numerous delay mechanisms involved in the entire chain: the delay between production and emissions of halocarbons, the time it takes for halocarbons to travel from the Earth's surface to the lower stratosphere, the delayed interactions between atmospheric dispersion and ozone depletion, and the delay between increased UV-B radiation and skin cancer incidence (skin cancer effects being related to long term exposure to UV-B radiation).

Moreover, the model enables the quantitative evaluation of long-term halocarbon production/consumption policies, in relation to concentration targets (such as the chlorine concentration targets as formulated by the WMO (1992)), and human health risk targets (such as the radiation risk target of VROM (1992)).

Recently, a simpler version of the UV-B chain model has been developed as a visualisation tool, which provides a clear and comprehensive overview of the ozone problem on one computer screen, and thereby enables the user to interactively develop a halocarbon production scenario (nine regions, and four CFC application sectors), and thereby evaluate the implications of these scenarios for ozone depletion and skin cancer incidence.

The UV-B chain model is an independent module of IMAGE (experimental version 1.6), and employs the halocarbon model and the UV-B impact model (*Figure 13.2*). The halocarbon model, as described in Chapter 10, consists of the following subsystems: the CFC-industry, CFC-consumption, landfill sites, the atmosphere (troposphere and stratosphere) and the Earth, as indicated by the lightly-shaded boxes in *Figure 13.2*. The key state variables (denoted by an s.index) of the five subsystems are: halocarbon production, halocarbon consumption, storage of halocarbons on landfill sites, atmospheric concentration of halocarbons and equilibrium tempera-

ture increase due to the changes in the concentrations of halocarbons. The subsystems of the model are coupled by processes (denoted by the term pr.index). The major processes are: transport/transfer, consumption, recycling, emissions, stratospheric transport and radiative perturbations. The simulation period defined for the halocarbon model is 200 years, from 1900 to 2100. In each iteration, the next state of the system is calculated, starting from the halocarbon production and proceeding to the main output of the halocarbon model, evaluating the equilibrium temperature increase associated with halocarbons (related to direct or overall radiative forcing due to halocarbons), and including global stratospheric chlorine concentrations.

The latter, i.e. chlorine concentration, forms the main input for the UV-B impact model, which, on a regional scale (for the Netherlands and the United States of America), calculates the resulting stratospheric ozone depletion, increased UV-B radiation levels, and the increased skin cancer risks (non-melanoma and melanoma skin cancer). For this model, the simulation period is 110 years, from 1990 to 2100, and the subsystems of the UV-B impact model (depicted by the dark shaded boxes in the *Figure*) include the atmosphere and the Earth. The key state variables are decreases in stratospheric ozone levels and skin cancer incidence, and the major processes are the changes in UV-B radiation levels, and the associated biologically-effective UV-B dose. In the following paragraphs, aspects of the UV-B impact model are described in turn and in more detail: stratospheric ozone depletion (section 13.3.2), UV-B radiation (section 13.3.3), and skin cancer incidence (section 13.3.4).

13.3.2 Stratospheric ozone depletion

Ozone losses are largely associated with increased atmospheric concentrations of chlorine and to a lesser extent with increases in bromine levels (WMO, 1992). Ozone depletion is expected to increase as long as the atmospheric levels of chlorine and bromine continue to increase. It is now gener-

Figure 13.2: Systems diagram of the UV-B chain model (coupled halocarbon/UV-B impact model)

ally accepted in scientific circles that the atmospheric chlorine concentration will reach a peak in the year 2000 if the London Amendments are adhered to. The expected rates of ozone depletion would be about 6% in summer and 10% in winter over the middle latitudes (WMO, 1992). These projections are based on calculations generated by atmospheric chemistry models incorporating currently known heterogeneous processes acting on sulphate aerosols, which faithfully simulate the observed ozone trend in middle latitudes in summer, but only half of the trend in winter. This discrepancy between the observed and simulated ozone trends might be a result of our incomplete knowledge of mechanisms such as: the local heterogeneous chemistry of stratospheric aerosols (as indicated by the elevated levels of chlorine monoxide (ClO) combined with the presence of sulphate aerosols at the altitudes of ozone depletion), and the transport of polar air which is both chemically-perturbed and robbed of its ozone to middle latitudes (WMO, 1992).

Because stratospheric ozone depletion is an extremely complex process involving a combination of a multitude of causes (see section 2.2.1), any simple analytical description is necessarily a crude one. For the purpose of this study, annually-averaged latitudinal stratospheric ozone losses are therefore assumed to be linearly and directly dependent on stratospheric chlorine concentrations. The major source of uncertainty inherent such an approach is the extremely simplified description of the atmospheric chemistry and transport processes in the lower stratosphere, although model studies indeed show that the ozone budget in the lower stratosphere is mainly controlled by the evolution of the chlorine-oxide chemistry, and is less affected by nitrogen-oxides or bromine related chemistry (c.f. Granier and Brasseur, 1992). Stratospheric ozone depletion (s.10 in Figure 13.2) is now expressed as:

$$\Delta O(\phi, t) = k(\phi)[Cl_x(t) - Cl_x(1970s)] \quad (13.1)$$

where $\Delta O(\phi, t)$ is the annually-averaged relative decrease in total column ozone at latitude ϕ at time t (%/year), ϕ is equal to 52°N

for the Netherlands, and 40°N, the averaged value at 40°N used for the United States of America (the two regions considered in the model), and where t varies over the period 1990 to 2100, and $Cl_x(t)$ is the global stratospheric chlorine concentration at time t (see Chapter 10, Equation (10.16)) (ppbv), while $Cl_x(1970s)$ is the global stratospheric chlorine concentration in the late 1970s during which no depletion of the ozone layer is assumed to have occurred (in accordance with the ozone trend for the northern middle latitudes found by analysis of historical data yielded by ground-level observations (Dobson) over the period 1955-1980. In the model the level is equal to 1.6 ppbv which corresponds to a tropospheric chlorine level of 2 ppbv in the same year (1977). Insofar as chlorine is concerned, in the international literature the 2-ppbv level is seen as the no-effect level, and the sustainable target for this factor in the scenarios aimed at stabilising climate change (see also Chapter 10) (Prather *et al.*, 1992). This level had already been reached by the late 1970s when the Antarctic ozone hole and the more modest ozone depletion observed over parts of the Northern Hemisphere were detected.

Finally, $k(\phi)$ is the latitudinally dependent coefficient (%/ppbv) based on the calibration of the trend in the simulated stratospheric chlorine concentration against the ozone trend over the last decade as calculated by Stolarski *et al.* (1991). The ozone trend is $-0.5 \pm 0.2\%$ /year at 50°N (approximates the ozone trend for the Netherlands at 52°N), and about $-0.45 \pm 0.2\%$ /year at 40°N (for the United States of America), which results in the latitudinal coefficients; $k(50^\circ N)$ at $4.9 \pm 2.0\%$ /ppbv, and $k(40^\circ N)$ at $4.3 \pm 2.0\%$ /ppbv.

The monthly thickness of the ozone layer ($O_m(\phi, t)$) at latitude ϕ at time t (Dobson Unit or DU¹) is now calculated as a linear function of the annual latitudinal change in the thickness of the layer of stratospheric ozone $\Delta O(\phi, t)$ (Equation (13.1)), and the monthly stratospheric ozone levels ($O_m(\phi, 1970s)$) in

¹ Total ozone abundance is normally specified in Dobson Units (DU) for specific points above the Earth's surface. 100 DU corresponds to an atmospheric column thickness of 1 mm at atmospheric pressure (1013 hPa) and a temperature of 298 K.

the late 1970s (the no effect levels at which no ozone depletion was assumed), as: $O_m(\phi, 1970s)c_m(\phi)\Delta O(\phi, t)$. Here $c_m(\phi)$ represents monthly factors at latitude ϕ correcting for seasonal variation in the ozone depletion, in the light of TOMS data. The initial stratospheric ozone abundance is described by means of a sine function, taking into account the natural seasonal variation of the ozone column. For the purposes of the model, 1990 ozone column has been given a reference value of 330 (DU), with a natural variation of 50 DU (Bowman, 1985).

13.3.3 Spectral UV-irradiance and effective UV dose²

The solar UV spectrum is strongly influenced by scattering associated with molecules and aerosols, and by absorptive properties of stratospheric ozone in particular, but also by clouds, tropospheric ozone and aerosols (the other UV-B influencing factors). As stated above, this study assumes the other UV-B filtering factors to remain constant, under which circumstances stratospheric ozone depletion would lead to increases in spectral UV-irradiance, and given no change in exposure habits, would also lead to increases in the effective UV-B dose. These processes are modelled as follows:

1. Spectral UV-irradiance

Latitudinal spectral UV-irradiances at the Earth's surface associated with stratospheric ozone depletion were calculated using de Leeuw's (1988) atmospheric UV-transfer model. This model takes account of the

absorption of solar radiation by ozone and aerosols, the scattering by air molecules and aerosols, the influence of clouds, and the reflection at the Earth's surface. The model includes an urban aerosol profile and a standard tropospheric ozone profile which remain unchanged in time. The atmosphere is modelled as a series of layers, and the calculated UV radiation at ground levels is reasonably consistent with the limited measurements of UV available at present (de Leeuw and Slaper, 1989). Although cloud cover is included in the model, for technical reasons all simulations with the model are run under clear sky conditions. The resulting distortion of the calculation of UV-radiation at ground level is subsequently corrected, as discussed in the next section.

2. Effective UV-dose

The wavelengths within the UV-spectrum differ strongly in their propensity to cause biological effects. The biological effectiveness of UV-B radiation in the region of 300 nm is about 1,000 to 10,000 times greater than that of UV-A radiation in the region of 350 nm. For this reason, it is common practice in biology, botany and medicine to combine UV-radiation intensity with a measure of biological effectiveness to form an action spectrum. Such an action spectrum is itself a weighing function, which makes it possible to add up the effective spectral UV-doses of different wavelengths arithmetically, and takes account of the biological process concerned, in this case photocarcinogenic effects on man. The annual carcinogenic effective UV-dose ($D(\Delta O, \phi, t)$ in mJ/cm², s.11) for an annual latitudinal change in stratospheric ozone thickness $\Delta O(\phi, t)$ at latitude ϕ and at time t is now calculated as the action spectrum (i.e. the weighted sum) of all spectral UV-doses (Slaper *et al.*, 1992):

$$D(\Delta O, \phi, t) = \sum_{\lambda=100}^{400} \left[\sum_{m=1}^{12} S_m(O_m, \phi, \lambda, t) \right] A(\phi, \lambda) \quad (13.2)$$

where λ is the UV-wavelength (range 100-400) (nm), $S_m(O_m, \phi, \lambda, t)$ is the total monthly spectral dose for month m and wavelength λ at latitude ϕ and at time t (mJ/(cm²)), $\Delta O_m(\phi, t)$ the monthly ozone thickness at lati-

² Throughout this chapter the following definitions are used (Slaper and Eggink, 1991):

- the radiance of a UV source is the total emitted radiative energy in the UV spectrum per unit of time and source area for a specific (solar) angle (in W/(cm²sr) or J/(s.cm².sr)).
- the UV-irradiance is the total radiative energy in the UV-spectrum reaching the (Earth's) surface per unit of time and surface area (in W/(cm²) or J/(s.cm²)).
- the spectral UV-irradiance is the UV-irradiance for a small wavelength interval, or wavelength (in W/(cm²) or J/(s.cm²)).
- the UV-dose is the total radiative energy in the UV-spectrum received per unit of surface over a certain time period (here a year) (in J/cm²).
- the spectral UV-dose is the UV-dose for a small wavelength interval, or wavelength (in J/(cm²)).

tude ϕ and at time t (DU), and $A(\phi, \lambda)$ is the relative effective weight factor at wavelength λ at latitude ϕ (action spectrum). Since no action spectrum for photocarcinogenesis on man is available, the action spectrum calculated for photocarcinogenesis in the hairless mouse was used, as in Slaper *et al.* (1992). This action spectrum, described in Sterenborg (1987) and Slaper (1987), is broadly similar to the action spectrum for erythema in human skin (Parrish *et al.*, 1982), and is therefore also used for humans. Figure 13.3 depicts this action spectrum, together with the updated action spectrum of carcinogenesis calculated by de Gruijl and van der Leun (1991), as described in Longstreth *et al.* (1991). Both action spectra are based on new definitions, which more adequately reflect the information that has become available on UV carcinogenesis in the hairless mouse, following the 1989 UNEP report (UNEP, 1989). The updated action spectrum created by de Gruijl and van der Leun (1991) is slightly different from Sterenborg's (1987) and Slaper's (1987) which is used here. A comparison between the two action spectra can be made by studying their associated radiation amplification factors (RAFs), an RAF being defined as the change (fractional differential) in the effective daily UV-dose relative to the change (fractional, negative differential) in the total ozone column (Madronich *et al.*, 1991). The

RAF factors indicate only relative changes in potentially effective UV-B radiation, and do not represent the absolute sensitivity of biological processes since the latter also depend on other factors including repair mechanisms (see next section). Kelfkens *et al.* (1990) found an RAF factor of 1.5 for the action spectrum described by Sterenborg (1987) and Slaper (1987), which is about 7% higher than the RAF factor of 1.4 associated with de Gruijl and van der Leun's (1991) action spectrum (Madronich *et al.*, 1991). Nevertheless, both carcinogenic action spectra imply a downgrading of the risk assessment of ozone depletion since the 1989 UNEP report, in which an RAF factor of approximately 1.6 was quoted (UNEP, 1989).

For melanoma skin cancer no action spectrum has yet been determined. For the purpose of this study, it is assumed that the action spectrum for melanoma induction is similar to the action spectrum for the induction of non-melanoma skin-cancers. This assumption will be further discussed in the next section.

In Slaper *et al.* (1992) a regression model was developed to approximate Equation (13.2). This was based on the outcomes of a series of simulation runs with the atmospheric UV-transfer model (de Leeuw, 1988). For each run, the annual total stratospheric ozone abundance was varied between 220 and 380 DU (corresponding to a change in

Figure 13.3: Action spectrum for UV photocarcinogenesis in the hairless mouse (Sterenborg, 1987; Slaper, 1987).

annual stratospheric ozone levels of $\pm 15\%$, compared with the stratospheric ozone levels in the late 1970s), and all monthly spectral UV-irradiance data at 52°N (the Netherlands) and 40°N (the United States of America) were calculated using the UV-transfer model, and the sum of the monthly totals was subsequently used in Equation (13.2) to calculate the carcinogenic UV-dose in the year concerned. The regression analysis resulted ultimately in a fourth order polynomial fit for the annual carcinogenic UV-dose $D(\Delta O, \phi, t)$ (s.11) as a function of the year's decrease in stratospheric ozone levels for the Netherlands and the United States:

$$D(\Delta O, \phi, t) = \sum_{n=0}^4 b_n(\phi) \Delta O(\phi, t)^n \quad (13.3)$$

where $b_0(52^\circ\text{N})$, $b_1(52^\circ\text{N})$, $b_2(52^\circ\text{N})$, $b_3(52^\circ\text{N})$ and $b_4(52^\circ\text{N})$ (in mJ/cm^2) are equal to 51557, 662.2, 10.25, 0.039 and 0.005696, and $b_0(40^\circ\text{N})$, $b_1(40^\circ\text{N})$, $b_2(40^\circ\text{N})$, $b_3(40^\circ\text{N})$ and $b_4(40^\circ\text{N})$ (in mJ/cm^2) are equal to 77432, 962.3, 14.31, 0.09652 and 0.007583, respectively. For the Dutch 1990 situation, the seasonal variation in the variation in the ozone depletion trend over the last decade (Stolarski *et al.*, 1991), and the calculated effective UV-doses for the 1990 total ozone column of 330 DU are depicted in Figure 13.4.

13.3.4 Skin cancer incidence

In general, it is believed that cumulative, long-term exposure of human skin to UV-B is associated with the development of skin cancer. Information relating to the dose-response relation is obtained from experiments on animals and from epidemiological data collected at various latitudes.

In modelling the incidence of skin cancer two steps must be considered:

Firstly, the actual effective dose received by the skin is calculated as a fraction of the total available solar effective UV-dose at the Earth's surface ($D(\Delta O, \phi, t)$, Equation (13.3)). This fraction, which is referred to as: the exposure fraction β , is dependent on the individual lifestyles with respect to UV exposure. In the model, the population is divided into twenty age-groups at five year intervals: 0..4, 5..9, 10..14, ..., 90..94, >95, denoted as $a=1,2,3,\dots,19,20$, respectively. Now the effective UV dose ($E(\Delta O, \phi, t, l(a))$) received by the skin for a person from age-group a at time t and at latitude ϕ (mJ/cm^2), where $l(a)$ is the age of a person in agegroup a ($= 5(a-1)+2$) is modelled as a fraction of the available solar effective UV-dose:

$$E(\Delta O, \phi, t, l(a)) = \beta(a) D(\Delta O, \phi, t) \quad (13.4)$$

where $\beta(a)$ is the exposure fraction received by the most exposed parts of the skin (head and hands) of persons in age-group a . Here

Figure 13.4: Seasonal variation in effective monthly UV-dose and ozone depletion (TOMS) in the Netherlands (Slaper *et al.*, 1992)

— UV 52°N
 - - - - TOMS ozone depletion

this parameter is assumed to remain constant over all age-groups, and is equal to 0.02.

As mentioned in section 13.2.3 the calculations of the UV-doses involved the assumption of cloudless conditions, and the calculated $D(\Delta O, \phi, t)$ therefore represents an overestimate of the actual annual dose reaching the Earth's surface. If the effects of clouds were taken into account, the UV-doses would be reduced to 65% of the clear-sky figures, and thus an exposure fraction $\beta(a)$ of 0.02, as assumed in the model, corresponds with a actual fraction of 0.03. This actual fraction corresponds to the observed average exposure experienced by indoor workers in the Netherlands (Slaper, 1987). In section 13.4.5, results of the influence of changing values of this parameter, representing changes in the propensity of individuals to expose themselves to the sun will be analysed.

Secondly, the cumulative number of skin cancer cases until age a at time t at latitude ϕ (cumulative incidence $Y_s(\Delta O, \phi, t, a)$ in cases per million) involving skin cancer type s ($s=1$: BCC; $s=2$: SCC; $s=3$: MSC) is calculated as a function of the cumulative, long-term UV-B exposure (Slaper *et al.*, 1986; 1992):

$$Y_s(\Delta O, \phi, t, a) = \gamma_s \left[\sum_{j=1}^a E(\Delta O, \phi, t-l(j), j) \right]^{c_s} l(a)^{d_s-c_s} \quad (13.5)$$

where $E(\Delta O, \phi, t-l(j), j)$ is the effective UV-dose received by a person at agegroup j at time $t-l(j)$ (mJ/cm^2)³, γ_s is the calibration coefficient estimated according to the skin cancer type, the sensitivity of the population, and the skin area exposed, and is estimated on the present incidence ($\text{cm}^2/(\text{year} \cdot \text{mJ})$,

Table 13.1: The values of the parameters c_s and d_s (Slaper *et al.*, 1992).

skin cancer type	c_s	d_s
basal cell carcinoma	1.5 ± 0.4	4.9
squamous cell carcinoma	2.5 ± 0.7	5.7
melanoma skin cancer	0.6 ± 0.3	4.7

while c_s , and d_s are skin cancer type-dependent model parameters describing the dose dependence and time dependence, respectively. The parameter c_s , which in the literature is often referred to as the biological amplification factor (BAF); refers to the fact that a 1% increase in effective UV-dosage leads to a $c_s\%$ increase the incidence of skin cancer.

In order to arrive at parameters for both basal and squamous cell carcinoma (BCC and SCC) the epidemiological data for skin cancer incidence derived from the third national skin cancer survey in the USA (Scotto *et al.*, 1981) were referred to. Observed skin cancer incidence data was used to estimate c_s , in combination with a correction for the action spectrum (Sternberg, 1987); Slaper, 1987), as described in Kelfkens *et al.* (1990) and Slaper *et al.* (1992). The parameter d_s is based on epidemiological evidence of age-specific incidences. Table 13.1 sets out the values of these parameters for BCC and SCC.

With respect to melanoma skin cancers (MSC), the relationship between UV exposure and actual incidence is somewhat ambiguous. No action spectrum has yet been determined and the fraction of UV-induced melanoma is not clear, a fact mainly due to incomplete knowledge of the relation between ozone depletion and the development of melanoma skin cancer. As mentioned in the previous section, the action spectrum for melanoma induction is assumed to resemble the action spectrum for the induction of non-melanoma skin-cancers. The dose-response parameter c_s for melanoma skin cancer has been estimated on the basis of epidemiological data obtained at

³ Although the model's simulation time period is from 1990 up to 2100, for the calculation of the cumulative UV-B exposure experienced a person belonging to age group a , obviously requires effective UV-B data for the period leading up to 1990. Since there are no physical observations available to provide data, estimates were derived from model-calculation over the period 1900-1990, whereby the stratospheric ozone depletion starts at the late 1970s, in accordance with the historical ozone trend adopted for the Dobson instruments (WMO, 1992), and given that the exposure fraction remained unchanged over the entire period 1900-1990.

various latitudes in the USA (EPA, 1987) (Slaper *et al.*, 1992). A 1% increase in UV reaching the Earth's surface is assumed to be associated with a 0.6% increase in melanoma skin cancer incidence. The age dependency parameter d_s was estimated on the basis of age-specific incidences for three separate birth-cohorts, as derived from EPA (1987) (Slaper *et al.*, 1992) (Table 13.1).

The values of the parameter c_s arrived at in Longstreth *et al.* (1991) are equal to 1.4 for basal cell carcinoma and 2.5 for squamous cell carcinoma, as determined from the updated action spectrum (de Gruijl and van der Leun, 1991), which are in close agreement with the values used in this study. The earlier estimates used in UNEP (1989), namely: 1.7 and 2.9, respectively, were based on uncorrected epidemiologic data pertaining to the fair-skinned population in the United States (Scotto *et al.*, 1981). In Longstreth *et al.* (1991) and UNEP (1989), approximate skin cancer risk estimates were calculated for a 1% ozone depletion by combining the RAF and BAF factors. Longstreth *et al.* (1991) estimate that a 1% ozone depletion will increase BCC incidence by $2.0 \pm 0.5\%$, and SCC incidence by $3.5 \pm 1.0\%$, which is somewhat less than the 2.7% and 4.6% envisaged in UNEP (1989). This lower estimate is due to the new definition of the carcinogenic action spectrum (de Gruijl and van der Leun, 1991), which downgraded both the RAF factor and the BAF factor. Having adopted a ratio of 4:1 for BCC vis-à-vis SCC based on earlier studies, Longstreth *et al.* (1991) estimated that a 1% depletion of ozone would lead to a $2.3 \pm 0.4\%$ increase in non-melanoma skin cancer incidence.

The state variable for annual skin cancer incidence ($I_s(O, \phi, t)$ in millions cases (s.12)) is described as:

$$I_s(\Delta O, \phi, t) = N(1, t) Y_s(\Delta O, \phi, t, 1) + \sum_{a=2}^{20} N(a, t) \left[Y_s(\Delta O, \phi, t, a) - Y_s(\Delta O, \phi, t-1, a-1) \right] \quad (13.6)$$

where $N(a, t)$ is the number of people in age group a at time t (in millions).

The state variable total mortality rate

($M_s(O, \phi, t)$ in cases (s.13)) is calculated as:

$$M_s(\Delta O, \phi, t) = \sum_{s=1}^3 l_f I_s(\Delta O, \phi, t) \quad (13.7)$$

where l_f represents the lethal fractions of the skin cancer type s ($s=1$ (BCC): 0.003; $s=2$ (SCC): 0.03; $s=3$ (MSC): 0.25).

13.4 Results

13.4.1 Introduction

The results are based on the following three halocarbon scenarios: the IPCC-1990 Accelerated Policies scenario (AP90 scenario), the WMO reference scenario (London Amendments), and the Copenhagen Amendments (see Chapter 10 for a detailed description). The results presented in this section are on a global scale and conform to the time scale (1900-2100) in case of the model outcome of the halocarbon model, and are on a regional scale (the Netherlands) whereby the time scale (1990-2100) conforms the model outcome of the UV-B impact model. Because of a lack of detailed data on incidence in the United States, this section presents no skin cancer incidence projections for this country. Hitherto, the only estimates for the US have been approximate and based on simulation experiments with the model, as described in Slaper *et al.* (1992).

The skin cancer incidence projections presented in this section are all expressed in terms of excess rates of skin cancer (or death due to skin cancer), defined as the extra number of skin cancer cases or deaths due to skin cancer per year expected as a consequence of stratospheric ozone depletion.

Ozone targets - In the analysis, the same ozone targets are used as in Chapter 10.

Health risk target - Although no mortality risk targets regarding skin cancer due to ozone depletion have yet been determined, the health risk target adopted here is the maximum mortality risk target for substances and sources of ionized radiation of 10^{-6} (1 per million per year), as recommended by the Dutch Ministry of the Environment (VROM, 1992). A mortality risk of 10^{-6} annually can

be viewed as an upper limit beyond which health risks become unacceptable.

13.4.2 Atmospheric chlorine concentration

Figures 10.10a and 10.16a (Chapter 10) depict the global atmospheric chlorine concentration for the three scenarios, as calculated using the IMAGE halocarbon model (experimental version 1.6). In this Figure, three ozone risk areas were identified which indicate the potential ozone risk with respect to atmospheric chlorine loading; a maximum ozone risk area (>3 ppbv), a high ozone risk area (>2 and <3 ppbv), and low/moderate ozone risk area (<2 ppbv). The AP90 scenario is a maximum ozone risk scenario (atmospheric chlorine concentration above 3 ppbv level), and atmospheric chlorine concentration which only declines in the case of the reference scenario (London Amendments) and the Copenhagen Amendments, reaches the 3 ppbv-level in about 2020-2040, and the 2 ppbv-level around 2060-2070, and thus tends to a low/moderate ozone risks in the second half of the next century. However, the London Amendments, as well as Copenhagen Amendments are, nevertheless associated with maximum ozone risks for the coming three to five decades.

13.4.3 Ozone depletion and UV-B radiation

The stratospheric ozone losses at 50°N (which closely approximate the Dutch situation at 52°N) for the three scenarios are depicted in Figure 13.5. This Figure also charts the ozone implications for the IPCC-1990 Business-as-Usual scenario and Low Emissions scenarios. Initial stratospheric ozone depletion in 1990 is simulated to be about 7%, which corresponds reasonably to the negative ozone trend of about 3-4% per decade as observed by the Dobson network over the period 1970-1991, and evidently, because of the calibration technique, also corresponds to the negative ozone trend over the last decade as detected by the TOMS measurements. The reference scenario and the Copenhagen Amendments show a decrease in ozone depletion in the next century, whereas the AP90 scenario (and the other IPCC-1990 scenarios) show large stratospheric ozone reductions.

13.4.4 Skin cancer incidence and mortality rates due to ozone depletion

Future skin cancer incidence and the associated mortality rates associated with ozone depletion also depend on the following factors:

- the sensitivity of the population
- changes in exposure habits

Figure 13.5 Stratospheric ozone depletion for the IPCC-90 scenarios, the reference scenario, and the Copenhagen Amendments at 50°N .

- Business-as-Usual scenario (partial Montreal Protocol)
- ... Low Emission scenario (Montreal Protocol)
- .-.- Accelerated Policies scenario (phase-out 2000, growth alternatives)
- reference scenario (London Amendments)
- Copenhagen Amendments

- changes in the rate of stratospheric ozone depletion

- the age distribution of the population

Moreover, the size of the population affects the absolute number of cases.

The sensitivity of the Dutch population to solar radiation is not likely to change in future, and therefore not examined here. The influence of the two factors, changing exposure habits and a change in the rate of stratospheric ozone depletion will be studied in the sensitivity analysis (section 13.4.5). The age distribution and size of the population will certainly change over the years. The effects of these changes are evaluated by adopting a population middle scenario for the Netherlands (CBS, 1990), as described in the paragraph 'Dutch population scenario' here below. But firstly, the paragraph 'Constant 1990 Dutch population' presents the skin cancer incidence projections for a standardized population, namely: the 1990 age-distribution in the Netherlands (hereafter referred to as: the constant 1990 Dutch population). This has been done to enable the effects of ozone depletion on skin cancer incidences to be distinguished from the combined effects of ozone depletion and a changing population on skin cancer incidence (see hereafter in paragraph named 'Dutch population scenario').

Constant 1990 Dutch population

A number of questions are first addressed to enable calculation of the present ozone contribution to the present skin cancer incidence as assumed in the model, to reveal the dynamics of the UV-B impact model, and to test the validity of the model. Finally, future skin cancer incidence projections for the four halocarbon scenarios are calculated. All these cases are studied under the assumption of constant 1990 Dutch population (total population size 15 million).

Question 1: Is there already a noticeable influence on ozone depletion to present total Dutch skin cancer incidence?

In order to answer this question the UV-B impact model is run without stratospheric ozone depletion over the period 1900 to 1990,

and the final simulated 1990 incidences for the three types of skin cancer, namely 966 per million (BCC), 95 per million (SCC) and 79 per million (MSC) are compared with the present 1990 incidences, as assumed in this study, namely 1000 per million (BCC), 100 per million (SCC) and 80 per million (MSC). This comparison clearly shows that the simulated skin cancer incidence fraction due to present stratospheric ozone depletion above the Netherlands is rather small: about 3% for BCC, about 5% for SCC and about 1.5% for MSC, which is in accordance with the expectations of the experts that there is a time delay of several decades between the time of increased UV-B levels (due to a 7% stratospheric ozone depletion in 1990) and the development of skin cancer.

Question 2: How long does it take before increased UV-B radiation associated with ozone depletion results in an extra skin cancer incidence?

In order to calculate the duration of the time-delay between increased UV-B levels and the development of skin cancer (related to long-term exposure), the UV-B impact model is run for a hypothetical, discontinuous stratospheric ozone depletion of 0% over the period 1900-1990, and 1% thereafter (this case is hereafter referred to as: the 1% ozone reduction case). In this case, the calibration parameter γ_3 is used to fit the simulated 1990 incidences with the 1990 incidences as assumed in this study. The resulting simulated excess rates for the three skin cancer types are given in *Figure 13.6*. This Figure clearly shows these time-delays, since the increase in excess skin cancer rates will be slowing down after 2045 (50 years after the sudden ozone decrease), and reaches the maximum values or equilibrium values around 2070 (the averaged life expectancy of a Dutchperson being about 70-75 years).

Question 3: How do the model outcomes relate to the incidence estimates presented by the UNEP (validity of the model)?

In order to test the validity of the model, the final simulated equilibrium skin cancer inci-

Figure 13.6 : Excess rates of basal cell carcinoma (BCC) and squamous cell carcinoma (SCC) and melanoma skin cancer (MSC) due to the hypothetical discontinuous ozone depletion for the Netherlands (the 1% ozone reduction case).

dences of the 1% ozone reduction case model are compared with the skin cancer incidence projections for a 1% ozone depletion, as presented by UNEP (Longstreth *et al.*, 1991). The simulated values (1% ozone reduction case) correspond with an increase in the incidences of approximately 1.95% for BCC, 3.3% for SCC, and 0.8% for MSC associated with 1% ozone reduction. In the UV-B impact model, the RAF factor (as calculated conform the simulated increase in effective UV dose for the 1% ozone reduction case) is equal to 1.3. By combining this RAF factor with the BAF factor of 1.5 for BCC, 2.5 for SCC, and 0.6 for MSC as incorporated in the UV-B impact model (see Table 13.1), the simulated equilibrium values can be generated.

The skin cancer incidence estimates presented by UNEP (Longstreth *et al.*, 1991) consistently refer to equilibrium incidence projections as a result of a 1% or 10% stratospheric ozone reduction (see also section 13.3.4). Longstreth *et al.* (1992) give an increase of $2.0 \pm 0.5\%$ and $3.5 \pm 1.0\%$ in BCC and SCC incidence due to a 1% depletion of ozone, respectively, figures which are based on an RAF factor of 1.4, and a BAF factor of 1.4 for BCC and 2.5 for SCC (de Gruijl and van der Leun, 1991). The small differences in BCC and SCC projections generated by UNEP and by the UV-B impact model can be explained by our lower RAF factor of 1.3 (compared to 1.4 adopted by

Longstreth *et al.* (1992)) and our higher BAF factor for BCC of 1.5 (compared to 1.4 in Longstretch *et al.*). Our BAF factor for SCC is the same as UNEP's.

Based on a BCC to SCC ratio of 4:1, Longstreth *et al.* (1991) calculated that a 1% ozone depletion results in a $2.3 \pm 0.4\%$ increase in the incidence of non-melanoma skin cancer, which is slightly higher than our 2.25%.

Finally, as regards melanoma skin cancer incidence, no comparison can be made, since Longstreth *et al.* offer no incidence estimates, arguing that quantitative knowledge about the relation between ozone depletion and the development of melanoma skin cancer is believed to be insufficient (see section 13.3.4).

In conclusion, the simulated equilibrium skin cancer incidence estimates associated with a 1% ozone reduction for the UV-B impact model are in accordance with the estimates given by UNEP.

Question 4: What are the skin cancer incidence implications for the three halo-carbon scenarios in the case of the Netherlands (constant Dutch 1990 population)?

The experiments reported above yielded insights into the dynamics and the validity of the model. The next step is to calculate the excess rates in non-melanoma carcinoma

Figure 13.7: Excess rates in non-melanoma carcinoma for the three scenarios in the Netherlands (constant 1990 Dutch population).

----- Accelerated Policies scenario
(phase-out 2000, growth alternatives)
———— reference scenario (London Amendments)
- · - · - Copenhagen Amendments

(BCC and SCC) and melanoma skin cancer (MSC) over the period 1990 till 2100 for the three scenarios (see Table 13.2). Figure 13.7 depicts the results for the excess rates of non-melanoma skin cancer for the three halocarbon scenarios. The excess rate of non-melanoma carcinoma increases from about 48 per million (BCC:SCC = 7:1) in 1990 till 289 per million in 2100 for the AP90 scenario, which is a sixfold increase. For the reference scenario and the Copenhagen Amendments, the excess rate peaks at 3 to 4 times present levels by the year 2040 (40 years after the peak in

stratospheric ozone losses. This peak around 2040 was to be expected in view of the time-delays of 40-50 years, as shown in the previous calculations (question 2). The excess rates of melanoma skin cancer exhibit a similar trend. Thus, for the AP90 scenario the excess rates for melanoma skin cancer (BAF factor is 0.6) are about 5 times higher than the 1990 levels (1.4 per million). According to the WMO reference scenario and the Copenhagen Amendments, the excess rate of melanoma peaks to 3 times present level around the year 2040.

Figure 13.8 compares the calculated

Figure 13.8: Excess mortality rate for the three scenarios in the Netherlands (constant 1990 Dutch population) (dark shaded area indicates where health target of 10^{-6} (1 per million) is exceeded)

----- Accelerated Policies scenario
(phase-out 2000, growth alternatives)
———— reference scenario (London Amendments)
- · - · - Copenhagen Amendments

Figure 13.9: Dutch population for the three age groups over the period 1950 to 2050 (CBS, 1990).

excess mortality rates for the constant 1990 population case with the health risk target of 10^{-6} (1 per million) for the three halocarbon scenarios. In the case of the reference scenario, the peak value of the excess mortality rate is about 2.5 times present levels. In this Figure, a high health risk area is identified where the mortality rate exceeds this target. From this Figure, it appears that the AP90 scenario begins to fail to meet the health risk target in 1995, and it also apparent that even according to the two other scenarios, it is not possible to achieve the health risk target of 10^{-6} ; the target is exceeded during the period from 1995 to 2095 (according to the reference scenario), and until 2085 (if the Copenhagen Amendments are observed).

Dutch population scenario

Question 5: What are the skin cancer incidence implications according to the three halocarbon scenarios for the Netherlands (Dutch population scenario)?

Since skin cancer primarily manifests itself among older people, the same level of UV exposure would lead to higher incidences in an ageing population, than in a younger population. Over recent decades the Dutch population has indeed been ageing, and this trend is likely continue in the foreseeable future. This factor will certainly affect future skin

cancer incidence, and also the excess skin cancer rates. For this reason, this case examines the skin cancer incidences implications in the Netherlands using the middle population scenario adopted by the Dutch Central Bureau of Statistics (CBS) (CBS, 1990) over the period 1950-2050, and historical population data over the period 1950-1990. This data describes the size and the age-distribution (into the twenty age-groups as assumed in the model) of the Dutch population for the period 1950-2050 (see Figure 13.9). For the sake of clarity, this Figure shows only three age-groups (0-14 years, 15-64 years, and 65 plus). For the period 2050-2100, this case assumes a constant age distribution and population size, equivalent to the 2050-situation. Figure 13.9 clearly shows that the current ageing of the Dutch population is continuing into the future for this specific middle population scenario.

This ageing effect is thus associated with higher skin cancer and mortality rates (yearly cases per million), even in the theoretical case in which stratospheric ozone depletion is assumed to have been brought to a halt immediately after 1990 (no stratospheric ozone depletion case), as is shown in Figure 13.10. Evidently, the total incidence, expressed in terms of annual cases, actually exhibit relatively greater increases, due to the combined effects of ageing and population growth.

Excess rates in non-melanoma carcinoma

Table 13.2: Summary of the main model-outcomes of simulation runs using the UV-B impact model for case of the constant 1990 Dutch population and the Dutch population scenario, and the sensitivity analysis.

case	reference scenario	reference scenario	AP90 scenario	Copen-hagen Amendments	high exposure case	low exposure case	high ozone case	low ozone case
model-assumptions:								
population	scenario	constant	scenario	scenario	scenario	scenario	scenario	scenario
k	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9
β	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
model-outcomes:								
Excess mortality rate								
Peak value	3.8	2.4	6.4	3.1	6.6	1.9	5.7	2.1
Int.($>10^{-6}$) ¹	189	88	361	131	402	43	336	62
health target ²	-	2095	-	2100	-	2085	-	2095
Non melanoma carc. ^a								
2050	275	171	365	219	509	106	413	152
2100	105	58	472	69	208	34	154	60
Mela. skin cancer ^b								
2050	7.2	4.6	9.2	58	9.2	4.9	10.6	4.1
2100	2.7	1.6	12.0	1.8	3.5	1.8	4.0	1.6

^a present excess rate for non melanoma carcinoma: 48 cases per million.

^b present excess rate for melanoma skin cancer: 1.4 cases per million.

¹ Int.($>10^{-6}$): the integral of the excess mortality rate above the health target of 10^{-6}

² the date when the excess mortality rate returns to health target of 10^{-6} (in all cases the health target starts to be exceeded in around 1995).

and melanoma incidences associated with ozone depletion are also influenced by the ageing of the Dutch population, as shown in Table 13.2 and Figure 13.11. This Figure depicts the non-melanoma skin cancer rates

for the three halocarbon scenarios under the Dutch population scenario. The results presented in Figure 13.10 are considered as the base-line estimates: i.e. the incidences occurring when no depletion of ozone

Figure 13.10: Incidences of non-melanoma carcinoma and melanoma skin cancer and mortality rate (the no ozone depletion case).

Figure 13.11: Excess rates in non-melanoma carcinoma for the three scenarios in the Netherlands (Dutch population scenario).

----- Accelerated Policies scenario
(phase-out 2000, growth alternatives)
———— reference scenario (London Amendments)
- · - · - Copenhagen Amendments

occurs. Excess rates (i.e. those associated with ozone depletion), as presented in the Figure 13.11, are now obtained by subtracting the base line estimates from the total incidences obtained according to the various scenarios. In general, the excess rates of non-melanoma carcinoma and melanoma skin cancer are now about 60% higher compared to the estimates for the constant 1990 population case (thus 35-40% of the total excess rates in the case of the population scenario is due to ageing of the population). The total number of cases of non-melanoma carcinoma increases from about 48 per million

(BCC:SCC = 7:1) in 1990 up to 471 (BCC:SCC = 6:1) in 2100 for the AP90 scenario, which is a tenfold increase vis-à-vis 1990 levels. For the excess rates of melanoma skin cancer, the increase is 8 times the 1990 levels. The excess rates of non-melanoma carcinoma and melanoma skin cancer according to the reference scenario and the Copenhagen Amendments both peak around 2040 at a level 4-6 higher than 1990 levels, and although levels decline after 2040, they remain above present 1990 levels until 2100 (see Figure 13.11).

Figure 13.12: Excess mortality rate for the three scenarios in the Netherlands (Dutch population scenario) (dark shaded area indicates where health target of 10^{-6} (1 per million) is exceeded).

----- Accelerated Policies scenario
(phase-out 2000, growth alternatives)
———— reference scenario (London Amendments)
- · - · - Copenhagen Amendments

Figure 13.12 compares the excess mortality rates with the health risk target 10^{-6} (1 per million). This Figure makes it apparent that due to the ageing effects all three scenarios now fail to meet the health risk target of 10^{-6} , and starts to do so in 1995. In the case of the Copenhagen Amendments, the maximum excess mortality rate is about 25% lower than the maximum rate for the London Amendments, and according to the latter scenario the health risk target is achieved by the year 2100 (see also Table 13.2).

Finally, Figure 13.13 translates the information from Figures 10.10a and 10.16a, and Figure 13.12 into a picture that combines the ozone targets and health risk targets. In this Figure atmospheric chlorine concentration is given as a function of the excess mortality rate. Furthermore, six risk areas are defined as: a maximum ozone and health risk area (>3 ppbv and $>10^{-6}$); a maximum ozone and low/moderate health risk area (>3 ppbv and $<10^{-6}$); a high ozone and maximum health risk area (>2 ppbv; <3 ppbv and $>10^{-6}$); a high ozone and low/moderate health risk area (>2 ppbv; <3 ppbv and $<10^{-6}$); a low/moderate ozone and maximum health risk area (<2 ppbv and $>10^{-6}$); a low/moderate ozone and high health risk area (<2 ppbv and $<10^{-6}$). This Figure shows the maximum ozone and health risks implied by the AP90 scenario. The WMO reference case (London Amendments) explicitly demonstrates the

time-delay between the atmospheric chlorine concentration (peak in chlorine by 2000) and the excess mortality rate (peak around 2040). The atmospheric chlorine concentration reaches already the maximum ozone risk area in the mid-1980s (per definition), and will exceed the maximum ozone target level till around 2040, while the excess mortality rate starts to exceed the health risk target from 1995, onwards, and only tends to low health risks at the end of the next century. Among the various scenarios, only the Copenhagen Amendments achieve the low ozone and health risk area by the end of the next century, but even this scenario is nevertheless associated with maximum/high ozone risks for the first three decades after 1995.

13.4.5 Sensitivity analysis

A sensitivity and uncertainty analysis had already been performed on the halocarbon model of the UV-B chain model, as described in section 8.4. It was shown that the total uncertainty in the first part of the UV-B chain model (the halocarbon model), from the production of CFCs to the point where atmospheric chlorine concentration would be fairly small, and mainly associated with uncertainties regarding the atmospheric lifetimes of the CFCs concerned. Here a single factor straightforward sensitivity analysis is given for the UV-B impact model (the second

Figure 13.13: The three scenarios related to ozone and health targets in the Netherlands (Dutch population scenario)

- I maximum ozone and health risk area (>3 ppbv and $>10^{-6}$)
- II maximum ozone and low/moderate health risk area (>3 ppbv and $<10^{-6}$)
- III high ozone and maximum health risk area (>2 ppbv; <3 ppbv and $>10^{-6}$)
- IV high ozone and low/moderate health risk area (>2 ppbv; <3 ppbv and $<10^{-6}$)
- V low/moderate ozone and maximum health risk area (<2 ppbv and $>10^{-6}$)
- VI low/moderate ozone and high health risk area (<2 ppbv and $<10^{-6}$)
- Accelerated Policies scenario (phase-out 2000, growth alternatives)
- reference scenario (London Amendments)
- .-.- Copenhagen Amendments

part of the UV-B chain model), which examines how variations in various main model parameters representing the processes of ozone depletion, effective UV-B radiation, and skin cancer development, affect the final outcome, namely: the excess rates of the incidence of skin cancer. The calculations in the analysis are all based on the WMO reference case (London Amendments) and on the Dutch population scenario, and the results are presented in *Table 13.2* (see page 211). The results of excess mortality rate are presented in terms of its peak value, the integral of the excess mortality rate above the health target of 10^{-6} , and the date when the excess mortality rate once more achieves the health target (in all cases the health target is no longer achieved from around 1995 onwards). These three indicators express how long, and to what extent, a case in the analysis is expected to fail to meet the health target. The results for the WMO reference scenario (in combination with the Dutch population scenario), reference scenario (under constant Dutch population), AP90 scenario (Dutch population scenario), and the Copenhagen Amendments (Dutch population scenario) are also presented in *Table 13.2*.

Question 6: What would the likely effect of a future change in exposure habits be?

When studying the influence of exposure

habits on the skin cancer risk estimates, the exposure fraction parameter β (present value of 0.02) is varied by $\pm 50\%$ over the period 1991-2100. *Figure 13.14* depicts the excess mortality rate for the three cases: the low exposure case, $\beta=0.01$; reference case, $\beta=0.02$; and high exposure case, $\beta=0.03$ according to the WMO reference scenario. The results as presented in *Table 13.2* show that a change in exposure habits would mainly affect the excess incidence rate of non-melanoma carcinoma: an increase of 85-100% for the high exposure case, and a decrease of 65-70% for the low exposure case, vis-à-vis reference case, whereas insofar as melanoma skin cancer is concerned, the effect is an increase or decrease of about 30-40% for the high exposure and low exposure case, respectively. This difference can be explained by the higher BAF factor for non melanoma carcinoma (NMC), which implies that the same change in effective UV dose would have a greater effect on NMC incidence than on MSC incidence. The excess mortality rate is also either increased or decreased by some 50-65% in the high exposure and low exposure case, respectively. The low exposure case sees the health target being achieved by 2085, which is also 15 years before the date of the target envisaged in the Copenhagen Amendments. A further comparison between the low exposure case and the Copenhagen

Figure 13.14: Excess mortality rates due to change in future exposure habits for the reference scenario (London Amendments) (dark shaded area indicates where level of 10^{-6} (1 per million) is exceeded).

----- $\beta = 0.03$ (high exposure case)
 ————— $\beta = 0.02$ (reference scenario)
 - · - · - $\beta = 0.01$ (low exposure case)

Amendments shows that in the low exposure case, the peak of the excess mortality rate is 40% lower, and the integral of the excess mortality rate is 75% lower. An opposite pattern appears when the high exposure case and the AP90 scenario are compared.

The conclusion which must be drawn is that a change in lifestyle leading to a reduction in the exposure of human skin to UV radiation would largely reduce the excess incidence and mortality rates, and in any case have a more significantly mitigative effect on the excess skin cancer incidence rate than an accelerated phase-out of CFCs and their alternatives, especially in the short-term.

Question 7: What would the effect of different future ozone depletion rates be?

The next aspect to be studied is the effect of uncertainties in future ozone depletion rates on the excess skin cancer incidence rate. This has been done by varying the coefficient $k(50^\circ\text{N})$ of Equation (13.1) (present value of $4.9 \pm 2.0\%$ /ppbv), between its maximum value of 6.9% /ppbv (referred to as: high ozone case) and its minimum value of 2.9% /ppbv (referred to as: low ozone case). The resulting calculated ozone depletion now peaks at between 6 and 16% for the year 2000 (about 10% for the reference case). The

simulated excess incidence and mortality rates are about 45-50% higher than those associated with the reference case, with no significant difference between the excess rates of the non melanoma carcinoma and melanoma skin cancer (Figure 13.15 depicts the excess mortality rates). The latter uniformity was not expected in view on the difference in their respective BAF factors (see previous question), but could be explained by the fact that melanoma skin cancer incidence responds more rapidly to higher peak UV-B doses. To study this dependency of melanoma skin cancer on peak UV-B doses, the case of a high ozone depletion (high UV-B radiation peak by 2000) is compared with high exposure case (more moderate increase in UV-B radiation over the entire simulation period). In the high ozone case, the excess incidence rate for non melanoma carcinoma is 20% lower, but for melanoma skin cancer 15% higher. A similar pattern (lower excess NMC incidence rate and higher MSC incidence rate) is indicated when comparing the high ozone case with the AP90 scenario. These results suggest that melanoma skin cancer incidence is probably more affected by a high UV-B peak dose than by moderate increases in UV-B levels over a longer period.

Figure 13.15: Excess mortality rates due to change in different ozone depletion rates for the reference scenario (London Amendments) (dark shaded area indicates where level of 10^{-6} (1 per million) is exceeded).

----- $k(50^\circ\text{N}) = 6.9$ (high ozone case)
 ————— $k(50^\circ\text{N}) = 4.9$ (reference scenario)
 $k(50^\circ\text{N}) = 2.9$ (low ozone case)

13.5 Conclusions

The UV-B chain model has been developed for the purpose of relating halocarbon scenarios with their effects at each stage of the source-effect chain of the ozone problem, from the atmospheric concentrations of CFCs, atmospheric chlorine concentration, stratospheric ozone depletion, to the effects on skin cancer incidences and death rates. This model clearly shows the delay mechanisms at work in the source-effect chain. Conformance to the London Amendments (a phase-out of the production of CFCs by 2000) would lead to a peak in the atmospheric chlorine concentration by about 2000, in stratospheric ozone depletion by about 2005 (five years after the peak in chlorine), and to a peak in skin cancer by about 2045 (40-50 years after the peak in chlorine). The latter delay is mainly due to the fact that skin cancer incidences depend on the cumulative UV-B exposure suffered by an individual, and therefore increased UV-B levels due to stratospheric ozone depletion occurring at a given moment will result in high skin cancer incidences after 40-50 years.

Simulation runs on the UV-B impact model using a population scenario (for the period 1990-2100) demonstrate that the excess mortality rate due to skin cancer (defined as extra number of deaths per year as a consequence of ozone depletion) will exceed the high health risk target of 1 per million, as defined by VROM (1992), from 1995 onwards, and will be far from meeting this health risk target if the IPCC-1990 Accelerated Policies scenario and the London Amendments are adhered to. The London Amendments imply a high health risk scenario throughout the next century. Only if the Copenhagen Amendments are observed can the excess mortality rate meet the health risk target at the end of the next

century, and even this protocol implies a high health risk scenario throughout the next century.

The outcomes of the excess mortality rates, and also the excess rates in melanoma carcinoma and non-melanoma skin cancer are relatively dependent on the ageing of the Western population. In all scenarios, 35-40% of the excess mortality rates and the excess rates in skin cancer incidence associated with the ageing of the population. The simulated excess mortality rates for the London Amendments in combination with a standardized population distribution in future (constant 1990 population) would, for example, now return to the health risk target of 1 per million at the end of the next century.

To summarize, future increases in skin cancer incidence cannot be reversed, in view of the numerous delay mechanisms and the ageing of the population, and will probably peak around 2040-2050. However, as the sensitivity analysis in this study shows, a change in lifestyle leading to a reduction in human exposure to solar radiation could largely reduce the excess incidence and mortality rates.

Nevertheless, the main uncertainties in this problem arise from future ozone depletions, which will certainly highly affect the skin cancer incidences in future. An increase in the rate of ozone depletion by 40%, could increase the excess skin cancer incidence by 45-50%. Furthermore, model-calculations show that the incidence of melanoma skin cancer incidence is possibly more affected by a high UV-B peak dose than by moderate increased UV-B levels over a longer period. Therefore, the future peak in ozone depletion, expected around the year 2000 if the London Amendments are adhered to, could be of major importance for the coming skin cancer incidences in the next century.

14 Allocating constrained global carbon budgets on the basis of equity rules: towards control of future climate risks

This Chapter is based on: Elzen, M.G.J. den, Janssen, M.A., Rotmans, J., Swart, R.J., and Vries, H.J. de (1992a): Allocating constrained global carbon budgets: interregional and intergenerational equity for a sustainable world. International Journal of Global Energy Issues 4, no. 4, 287-301.

14.1 Introduction

An international response by means of a worldwide reduction in greenhouse gas emissions in order to reduce the anticipated risks of climate change is now considered appropriate by the majority of both developed and developing countries. Most of the OECD-countries have already issued declarations of intent, or have even already adopted policies, aimed at stabilizing or reducing their emissions of carbon dioxide as well as, in some cases, other greenhouse-gases. The risk of climate change is truly a global issue. If major risks are to be avoided, a worldwide reduction in the emissions of greenhouse gases is required, as the previous Chapters of Part IV have demonstrated. At the same time, however, almost all nations have adopted economic growth as their prime goal - in order to satisfy the increasing needs of their people and to keep their capital and labour resources in productive use. This Chapter deals with the development of an effective international response to climate change, which recognizes the present and historical iniquities between developing and industrialized countries.

From various quarters, it has been argued that past CO₂-emissions should be taken into account in any allocation of future CO₂-emissions. As Figure 14.1 shows, historical CO₂-emissions due to fossil fuel combustion and other industrial activities such as cement manufacturing are quite unevenly shared among the eleven world-regions as defined in this Chapter¹. The majority of past anthropogenic CO₂-emissions have occurred in

industrialized regions of the Northern Hemisphere. Current-annual emissions in these regions reach the level of 6 tonnes C (tC) per capita, whereas annual per capita CO₂-emissions in the developing regions are typically between 0.2 and 0.6 tC. It should be added that the rate of increase of emissions in developing regions is much larger, and their share in global emissions is expected to rise from 26 % in 1990 to about 35 % by the year 2025 for the four IPCC-1990 scenarios. To some extent, this has transformed the debate about a Convention on Climate Change into a north-south equity issue.

In this Chapter, the key question to be addressed is: how, given economic priorities, can the remaining global greenhouse gas emissions be allocated among the various nations/regions and what mechanisms can be instrumental to this purpose? Estimating and allocating a constrained global carbon budget is a question which has already been addressed by Krause *et al.* (1989) and Fujii (1990). Both studies approached the equity issue in a quantitative manner by reference to an atmospheric CO₂-concentration target. Krause *et al.* (1989) introduced the concept of a global carbon budget based on a 400 ppmv CO₂-concentration of bubble capping fossil-fuel CO₂-emissions between 1985 and 2100, and allocated allowable emissions using three types of equity formulas based

¹ Here the world is divided into eleven world regions: European Community, Rest of Western Europe, OECD East, Eastern Europe, GOS, North America, Latin America, Africa, Middle East, Centrally Planned Asia incl. China, and South/South East Asia incl. Australasia.

Figure 14.1: Regional CO₂-emissions due to fossil fuel combustion and cement production over the period 1800 till 1990 (Janssen et al., 1992)

on: present carbon emissions, carbon emitted per unit of economic activity (GNP) and per capita. The role of non-CO₂-greenhouse-gases and biospheric CO₂ releases was estimated indirectly. Fujii (1990) used a simple, analytical carbon cycle model to calculate future emission quota based on the equity criterion that every human being, past or future, is deemed to be associated with the same annual quatum over the whole period from 1800 till 2100. However, Fujii did not take the role of emissions from land use changes or other non-CO₂ greenhouse gases into account.

Several mechanisms have been proposed by which the allocation of a constrained global carbon budget could be facilitated. A worldwide increase in energy prices -

through a carbon tax, for example - appears an efficient instrument to curb CO₂-emissions, but would inhibit economic growth in many less-industrialized regions unless compensatory measures were taken. Under a system of tradeable emission permits, as one of the market-oriented instruments for controlling greenhouse gas emissions, developing countries would be provided with surplus permits that could be sold to industrialized countries (Grubb and Sebenius, 1991; Grubb, 1989). Alternatively, commitments from developing countries to curb their emissions or increase their energy efficiency could be compensated by special payments, possibly through a green fund fed by the revenue from an international carbon or energy tax.

Whatever the mechanism, a major implementation issue is the allocation of payments (or permits) to the different countries. As part of the attempts to set up a global Climate Change Convention, the process of finding appropriate indicators in which past, present and future greenhouse-gas-emissions play a role, is currently gathering momentum. Indicators for such an allocation could be based on present emissions, on area, on population levels (equal per capita carbon budget), on the state of the economy (equal global carbon budget per unit GNP), on energy intensity, or on a combination of such factors (Grubb, 1989; Krause *et al.*, 1989; Fujii, 1990).

This section evaluates long-term climate strategies by which the burden of mitigating climate change by controlling CO₂-emissions is shared equitably, and uses IMAGE (experimental version 1.6) to calculate the remaining global carbon budget. As a first step towards an allocation mechanism for the remaining carbon budget, an equal per capita carbon emission rate is assumed over the entire period from 1800 till 2100 using past and future population estimates. Such an interpretation of intergenerational and inter-regional equity throughout the world, enables the 'emission debts' of the industrialized regions to be calculated as the amount of carbon emitted since 1800 in excess of the 'rightful' regional share. These debts can be referred to when determining an initial allocation of future regional emission rights, which in turn can form the basis of a concept of tradeable emission rights.

The structure of this Chapter is as follows: section 14.2 presents the regional contribution to past rises in atmospheric CO₂ concentration. In section 14.3 the remaining carbon budgets are then presented for the IPCC-1990 scenarios and the Low-Risk scenario. Section 14.4 presents the emission debts and the allocation of the future carbon budgets (per capita emission quota) for the four IPCC-90 scenarios and the Low-Risk scenario.

14.2 Regional contributions to CO₂-concentration increase

Industrialized countries have contributed much more to past CO₂-emissions than the developing world has. Using the IMAGE-model, the contribution to the global rise in CO₂-concentration since 1800 associated with 11 world-regions is estimated, both from fossil fuel combustion and cement manufacturing (Darmstadter, 1971; Marland and Rotty, 1984; Marland, 1990; Marland *et al.*, 1989; Mitchell, 1981; 1982; 1983) and from land use changes (Houghton *et al.*, 1983; 1987; Houghton, 1991). Figure 14.2 shows these regional contributions as percentages of total simulated CO₂-concentration rise between 1800 and 1990. The relative contributions of Western-Europe and North-America amount to some 40%; Eastern Europe (including the former USSR) and Japan/Oceania (OECD East) have contributed 20% and 4% respectively. In all these regions, past combustion of fossil fuels is the major culprit. In contrast, the relative contributions of Africa, Latin America and South/South-East Asia - which exceed 30% - are for some 75% due to past deforestation. In the industrialized regions, emissions associated with deforestation occurred so long ago that much of the carbon has already been removed from the atmosphere - which explains the minor role of land use changes in these regions, which is reflected in Figure 14.2.

This outcome is to be expected. In the early development stages, agriculture dominates the economy and emissions are largely associated with deforestation. In the next stages of industrialization and rapid growth of per capita income levels, emissions from the combustion of fossil fuel rapidly surpass these biotic emissions. One would therefore expect to find a positive correlation between past emissions associated with fossil fuel combustion and cement manufacturing and the resulting relative contribution to the CO₂-concentration rise, and economic welfare as measured by GNP per capita. This correlation indeed turns out to be significant (Janssen *et al.*, 1992). Thus, present prosperity in the industrialized countries can be

Figure 14.2: Relative contribution of the 11 world regions to the rise in atmospheric CO₂-concentration over the period 1800-1990

said to be founded on large-scale CO₂-emissions in the past.

Most of the developing world is still at a stage in which large-scale land use changes occur as populations keep growing and increases in food production and export revenues are the goals being pursued. Consequently, their relative contribution to any rise in atmospheric CO₂-concentrations is largely associated with deforestation. From data on financial debts² for the 11 regions, it appears that the burden of financial debts is most heavy in Africa and Latin America. One might hypothesize that the developing regions are building up environmental debts (by exporting wood and agricultural products to the rich regions) to relieve financial debts (to the industrialized regions). Figure 14.3 shows the relative contribution to past rises in CO₂-concentrations associated with land use changes per unit of GNP versus the financial debt as a percentage of GNP. This graph is one way to represent the present predicament of the regions of Africa, Latin America and South/South-

East Asia: the squandering of their forests has become instrumental to the development of their economies and to feeding their growing populations.

14.3 The global carbon budget

In order to define the problem of emission debts and allocations, the atmosphere is considered as a sink which can only absorb a limited amount of greenhouse gases at a limited rate. The global carbon budget over the period 1800 to 2100 is defined as the total amount of carbon emitted during that period. It is equivalent to the cumulated historical CO₂-emissions and future CO₂-emissions from fossil fuel combustion, cement manufacturing and land use changes. This budget is a 'left-over': for non-CO₂-greenhouse-gases the emission time-paths are according to their descriptions as stated by the IPCC (1991b). The historical carbon budget is the same for each scenario: 346 GtC, consisting of 220 GtC³ associated with fossil fuel com-

² External debt data for most countries are obtained from the OECD and World Bank statistics (OECD, 1990; World Bank, 1990a; World Bank, 1990b; World Bank, 1989). For most of the developed countries which were excluded from the World Debt tables, rough estimates were made from IMF data (IMF, 1991) and data of the Economist Intelligent Unit (EIU, 1987). The GNP data were obtained from FAO (1990).

³ In Janssen *et al.* (1992) the detailed backgrounds of the calculated total CO₂-emissions due to fossil fuel combustion of 220 GtC over the period 1800 to 1990 (including 6 GtC for 1990) are given (see Figure 1). Based on data of Keeling (1990), and Marland (1990), the CO₂-emissions due to industrial sources are estimated at 213 ± 20 GtC for the period 1850-1989.

Figure 14.3: Relation between the relative contribution to the CO_2 -concentration rise by land use changes per unit of GNP and the external debt as percentage of GNP for the 11 regions in the world, (den Elzen *et al.*, 1992a).

EC	= European Community
RW Eur.	= Rest Western Europe
OECD E.	= OECD East
E. Eur.	= Eastern Europe
USSR.	= Former USSR
N. Am.	= North America
Lat. Am.	= Latin America
CPA	= Centrally Planned Asia
SEA	= South/South East Asia

bustion and cement manufacturing and 126 GtC^4 with land use changes (Janssen *et al.*, 1992).

Past and remaining budgets for the scenarios are listed in Table 14.1. The Low-Risk-scenario has the smallest carbon budget, i.e. 685 GtC of which about 338 GtC is still left to be dealt with in the future. For the IPCC-1990 Accelerated Policies (AP90) scenario, the global carbon budget amounts to about 800 GtC , and the remaining budget is 455 GtC . If the world community were to follow the high/extreme climate risk IPCC-1990 Business-as-Usual (BaU90) scenario, the global carbon budget would be an estimated 1970 GtC , of which 18% has been emitted so far. This would result in a remaining carbon budget of 1625 GtC . The other two scenarios have budgets which are in-between these extremes.

Actually, the carbon budget is dependent on the actual emission-path over time - a dependency that can be evaluated with the IMAGE-model. For example, if the BaU90

path is followed and in the year 2000 the world community decides to strive for the CO_2 -equivalent concentration target of 475 ppmv in 2100 as in the Low-Risk-scenario, such a switch would require a decrease of fossil CO_2 emissions to 70 % of the year 2000 level within 50 years. The resulting carbon budget amounts to 365 GtC , slightly higher than might be expected because the high emissions between 1990 and 2000 are partly absorbed before the time-horizon year 2100. If the decision to switch is taken in 2010, emissions from fossil fuels will have to drop by 90% in less than 10 years. The resulting carbon budget would decrease to 325 GtC . In these simulations, it is assumed that the emissions of non- CO_2 greenhouse gases will conform to the Low-Risk scenario after the decision to switch. If these gases were not controlled and the BaU90 scenario was followed, the global carbon budget would almost vanish. Therefore, the role of non- CO_2 gases is by no means negligible in any negotiating process on future budgets.

⁴ The calculations of the historical CO_2 -emissions due to land use changes, namely: 126 GtC , are described in Janssen *et al.* (1992), and are based on a bookkeeping model using data published by Houghton *et al.* (1983; 1987) and Houghton (1991). IPCC (1990) gives an 1850-1986 estimate of $117 \pm 35 \text{ GtC}$, and an averaged value of $1.6 \pm 1.0 \text{ GtC/yr}$ over 1980-1989. Our estimate over the period 1850-1986 amounts to 107 GtC , and an averaged annual value of 1.6 GtC over the period 1980-1989.

14.4 Emission debts and the allocation of future CO_2 -emissions

When it comes to allocating the remaining global carbon budgets, how should past emissions be evaluated? Has mankind in general emitted more carbon than it should

Table 14.1: Carbon budgets for the IPCC-1990 scenarios and the Low-Risk scenario (Rotmans and den Elzen, 1993a) under future population growth (CO_2 emissions from fossil fuel combustion, cement manufacturing, and land use changes).

Scenario	Past budget (GtC)	Remaining budget (GtC)	Q_{cap} (tC/cap.yr)	Emission debt (GtC)
Business-as-Usual scenario	346	1625	1.4	-190
Low Emission scenario	346	846	0.85	21
Control Policies scenario	346	646	0.71	75
Accelerated Policies scenario	346	455	0.58	127
Low-Risk scenario	346	338	0.49	159

have - or have specific regions done so? One way to approach this question is to calculate the global per capita emission budget which over the period 1800-2100 would exactly consume the global carbon budget, using past, present and projected world population data⁵. This per capita quatum approach has the advantage of being conceptually and computationally simple. It can be used to express an equality principle for the allocation of the emissions: *every human being has an equal emission quatum irrespective of both the country he or she lives in and the generation he or she belongs to* (Fujii, 1990). The need for a more elaborate approach which also reflects geographical and economical differences among regions is recognized.

This per capita quatum, to be interpreted as a permitted quantity of emissions per capita (Q_{cap}), can be expressed as:

$$Q_{cap} = \frac{\sum_{r=1800}^{1990} emCO_{2,his}(t,r) + \sum_{r=1991}^{2100} emCO_{2,scen}(t)}{\sum_{r=1800}^{1990} pop_{his}(t,r) + \sum_{r=1991}^{2100} pop_{scen}(t)} \quad (14.1)$$

⁵ The population data between 1800 and 1920 are based on Durand (1967). Over the period 1920 and 1990 the population data were obtained from the United Nations World Population Prospects (UN, 1966; UN, 1990). The future population is based on recent analyses of the World Bank (Bulatao *et al.*, 1990). Global population is assumed to increase from 5.3 billion in 1990 to 11.3 billion in 2100, mainly as a result of population growth in the developing countries.

where $emCO_{2,his}(t,r)$ are the historical CO_2 -emissions at time t for region r (GtC/year) and $emCO_{2,scen}(t)$ are the future CO_2 -emissions according to the scenario under consideration (GtC/year), while $pop_{his}(t,r)$ and $pop_{scen}(t,r)$ are the historical and future regional population sizes in year t and for region r , respectively.

Based on this per capita quatum, the global carbon budget under the AP90 scenario of about 800 GtC corresponds with a permitted emission per capita of 0.58 tC/year, using recent World Bank projections of population growth until 2100 (Bulatao *et al.*, 1990). Under the BaU90 scenario it amounts to 1.41 tC/cap.yr. For the other IPCC-1990 scenarios, Low Emission -, and Control Policies (CP90) scenario and the Low-Risk scenario, the per capita quatum is 0.71, 0.85 and 0.49 tC/cap.yr resp., whereby according to the scenarios, 85-90 % is due to fossil fuel combustion and cement manufacturing.

The (regional) emission debt is defined as the difference between the amount of carbon which is allowed to be emitted (by a region), based on the Q_{cap} for the scenario under consideration, and the actual (regional) cumulated emissions in the past. The emission debt ($ED(1990,r)$) can be described in mathematical terms:

$$ED(1990,r) = \sum_{r=1800}^{1990} emCO_{2,his}(t,r) - Q_{cap} * \sum_{r=1800}^{1990} pop_{his} \quad (14.2)$$

Using the quatum and carbon budget values of the AP90 scenario results in a global emission debt bequeathed by past generations to future generations of about 127 GtC. In other words, people living in the past were allowed to consume about 27% of the budget whereas they actually emitted 43%. The present generations and our ancestors have reduced emission quota for our descendants. Under the Low-Risk scenario, the emission debt amounts to 159 GtC, which is about 25 % higher than the emission debt under the AP90 scenario. If the world population grows according to the low projection levels (UN, 1992), the value of Q_{cap} is equal to 0.41 tC/cap/yr, and the emission debt will drop to 117 GtC because the budget is divided among fewer people. According to the high population projection ($Q_{cap} = 0.6$ tC/cap.yr), the global emission debt will rise to 189 GtC (Janssen *et al.*, 1992).

On the other hand, if the large carbon budget is available which is implicit in the high/extreme-risk BaU90 scenario, there would be an emission credit of 190 GtC. The emission debts for the other two IPCC-1990 scenarios are given in Table 14.1.

Using the above equations on a regional scale the emission debt for the different scenarios resulting from past CO₂-emissions (from fossil fuels, cement manufacturing and land use changes) can be allocated among

Table 14.2: Emission debt (in GtC) for four world-regions

Regions	AP90 scenario	Low Risk scenario
Western Europe	36	40
Eastern Europe	27	30
Rest of the Industrialized World	88	90
Developing World	-24	-1

the eleven world regions, as presented for the BaU90 and the AP90 scenario and the Low-Risk scenario in Figure 14.4.

The emission debts for the total CO₂-emissions in the case of the BaU90 scenario are presented in bar 1 in Figure 14.4. For this scenario, with its much larger global carbon budget, North America and the EC rank highest in terms of emission debts. In time, the emission credits for the Asian regions with large and still growing populations become quite large, as is to be expected in view of our definitions.

The resulting regional emission debts under the AP90 scenario are presented in Figure 14.4 (bar 2) and Table 14.2. The three industrialized regions are highly indebted to the future: 36 GtC for Western Europe, 27 GtC for Eastern Europe (including former

Figure 14.4: Regional emission debts for fossil fuel combustion and land use changes between 1800 and 1990, using different carbon budgets.

- EC = European Community
- RW Eur. = Rest Western Europe
- OECD E = OECD East
- E. Eur. = Eastern Europe
- USSR. = Former USSR
- N. Am. = North America
- Lat. Am. = Latin America
- CPA = Centrally Planned Asia
- SEA = South/South East Asia

- ▨ Business-as-Usual scenario (bar 1)
- ▨ Accelerated Policies scenario (bar 2)
- ▨ Low-Risk scenario (bar 3)

USSR), and 88 GtC for the rest of the industrialized world. The developing countries (fourth region) have built up an emission credit of 24 GtC.

The regional emission debts for the Low-Risk scenario are also presented in Table 14.2 and Figure 14.4.

When CO₂-emissions from fossil fuel combustion and cement manufacturing are considered in isolation, the global emission debt for the AP90 scenario amounts to 32 GtC. The four major world regions are still highly indebted, but now not so much to the future as to the developing world. The industrializing countries have built up an emission credit of 95 GtC if only fossil fuel combustion and cement manufacturing are considered, which shows that recent deforestation in Africa and Latin America has caused this emission credit to be transformed into an emission debt (den Elzen *et al.*, 1992a).

The next question is how the remaining global carbon budget should be distributed among the different regions and over time, taking into account past and present emissions of CO₂. A simple allocation mechanism for the remaining carbon budget is assumed, which encompasses two elements:

1. Only the CO₂-emissions, i.e. the remaining carbon budget as defined previously will be allocated in future;

2. distribution of this budget will be based on the equal per capita carbon budget criterion, i.e. an equitable share of future CO₂-emissions, taking into account the already emitted carbon in the past.

The emission rights ($ER(1990,r)$) consist of the allowable CO₂ emissions in the period 1991-2100, based on the equal emission quantum minus the emission debt built up in the past:

$$ER(1990,r) = Q_{cap} \sum_{t=1991}^{2100} pop_{scen}(t,r) - ED(1990,r) \quad (14.3)$$

Figure 14.5 summarizes the results of this approach based on the carbon budget (total CO₂-emissions from fossil fuels, cement manufacturing and land use changes) for the three scenarios (BaU90-, AP90- and Low-Risk scenario). The first bar represents present annual emissions per capita. For the high climate risk BaU90 scenario almost all industrialized regions and Latin America have emission rights per capita which are lower than present emission levels. According to this high scenario North America has emitted more CO₂ in the past than was allowed for the whole period, and ends up with negative permitted emission levels. This situation is worse in the case of the low/moderate climate risk scenarios, the

Figure 14.5: Regional emission rights per capita for fossil fuel combustion and land use changes for the period 1991-2100 using different carbon budgets.

EC	= European Community
RW Eur.	= Rest Western Europe
OECD E	= OECD East
E. Eur.	= Eastern Europe
USSR	= Former USSR
N. Am.	= North America
Lat. Am.	= Latin America
CPA	= Centrally Planned Asia
SEA	= South/South East Asia

- emission 1990 (bar 1)
- ▨ Business-as-Usual scenario (bar 2)
- ▩ Accelerated Policies scenario (bar 3)
- ▤ Low-Risk scenario (bar 4)

AP90 scenario and Low-Risk scenario, under which the regions, EC and CIS, end up with negative emission rights.

Most of the developing regions, however, have allowable emission levels per capita which are higher than the emission rights of the industrialized regions, but in some cases lower than present developing region emission levels.

14.4 Conclusions

The industrialized countries have so far caused the major part of climate change. Analysing past carbon emissions from fossil fuel combustion, cement manufacturing and land use change indicates that present wealth in the industrialized countries was paid for by large-scale emissions in the past. The relative contribution of Western Europe and North America to the CO₂-concentration rise over the period 1800 till 1990 is about 40%, almost completely due to fossil fuel combustion and cement manufacturing. The contribution from Africa, Latin America and South/South-East Asia - which exceeds 30% - is for some 75% due to deforestation.

Therefore, the industrialized world should take prime responsibility in responding to the challenges of climate change, and support the developing countries in their efforts to contribute their share in mitigating climatic change without arresting their development. As a consequence, the international policy discussion understandably involves economic north-south issues as well as the search for technical options. Under the premises of the IPCC-1990 Accelerated Policies scenario (reference case) the world would be constrained by a global carbon budget, defined as the cumulated CO₂-emissions from fossil fuel combustion, cement manufacturing and land use changes over the period 1800 till 2100, of about 800 GtC. About 43% of this budget has already been used up in the past. If all world citizens living in the period 1800-2100 were to be allocated with an equal emission quatum, this

would result in an annual per capita emission of 0.58 tC/cap (according to the most recent world population growth scenario), whereby the world would have exceeded its allocated budget for 1800-1990 by some 127 GtC ('emission debt'). On a regional scale, the emission debt for the industrialized world-regions amounts to: 36 GtC for Western Europe, 27 GtC for Eastern Europe, and 88 GtC for the rest of the industrialized world. The developing countries, however, have an emission credit of 24 GtC. These regional emission debts and credits increase the future per capita carbon budget for the developing regions by 0.2 - 0.8 tC/cap per annum; North America and the EC end up with a negative annual budget of 0.4 to 1.5 tC/cap respectively.

Even when the IPCC-1990 Business-as-Usual scenario is considered as a reference tool, the future emission quotas for most of the industrialized countries are lower than their current per capita emissions, e.g. North America has a negative annual emission right per capita of 0.3 tC/cap and an emission debt of 60 GtC.

Evidently thus, effective, preventive and adaptive response to climate change requires a concerted global effort. A successful global response to climate change has to acknowledge the disproportionately large contributions from the rich regions in 'filling' the global carbon sink. Finding a remedy requires that the debate moves from contention to dialogue. Equitable distribution of the burdens of response strategies has to be found, with proper respect for the striking unbalance between means and ends, between past and future. Ways and means of transferring technology, knowledge and funds from the industrialized countries to the developing countries and to the formerly centrally planned countries in Eastern Europe and the Soviet Union have to be explored and implemented. Such transfers should be based on both responsibility and capability. Only then can the world community expect a climate agreement to which both rich and poor regions are committed.

Part V Conclusions

15 Conclusions

This thesis describes an integrated assessment framework, namely: IMAGE: an Integrated Model to Assess the Greenhouse Effect (experimental version 1.6), consisting of the main modules (submodels) of IMAGE (version 1.6), and the UV-B chain model (coupled halocarbon/UV-B impact model). This integrated, multidisciplinary modelling framework is designed to sketch 'state-of-the-art' knowledge and expertise in a comprehensive overview. In this study the IMAGE model is used, firstly to identify and analyse some of the present main uncertainties in climate change and ozone depletion (*uncertainty analysis*), secondly to evaluate the implications of various climate and ozone strategies in light of future risks, and thirdly to develop preventive or ameliorative policies, which reduce risks to tolerable levels (*risk assessment: a target-oriented approach*).

Uncertainty analysis

Climate change

In the analysis of the coupled carbon cycle/climate model of IMAGE (experimental version 1.6) the quantitative role of biogeochemical feedbacks is assessed. The carbon cycle module of this coupled model consists of an ocean box-diffusion model, a terrestrial biosphere model, and an atmospheric model, and simulates the concentrations of CO₂ in the various components (the atmosphere, the terrestrial biosphere and the ocean). The following processes are modelled in the ocean model: transport of dissolved carbon by up- and downwelling, through turbulent mixing and through precipitation of dead organic carbon material, and atmospheric exchange processes. In the

biosphere model, carbon is consumed in the process of net primary production, and thus arrives in a particular ecosystem in one of the various biomass reservoirs (biomass, litter, humus and charcoal). Terrestrial feedbacks have also been incorporated in the carbon cycle model, namely: the CO₂ fertilization effect, and temperature-related feedbacks on net primary-production and respiration of soil and litter. The climate model, which is coupled to the carbon cycle model, is an energy balance box upwelling-diffusion model. Major limitations of this modelling approach are: distinction of only seven types of ecosystems, steady-state system assumption for the year 1760, exclusion of ocean circulation, the incidental linearization of complex system behaviour, feedbacks modelled by means of parameterized representations of complex biogeochemical and geophysical processes. In spite of these limitations and simplifications, this modelling approach yields useful insights, as the model experiments show:

- * a major part of our deficient knowledge about the sources and sinks of carbon can be ascribed to our incomplete knowledge about biogeochemical feedback processes within the carbon cycle;
- * exclusion of the feedbacks in our model would lead to an apparent net imbalance in the past and present carbon budgets;
- * the simulated CO₂ concentration for the IPCC-1990 Business-as-Usual scenario is significantly lower than the IPCC-1990 estimates (based on simulation experiments with carbon cycle models which take account of an unbalanced carbon budget): the difference in the year 2100, is about 16% from the 1990 level;
- * the IPCC-1990 'central estimate' value of the CO₂-concentration in 2100 falls outside the range of model outcomes generated

- using our balanced modelling approach;
 - * the CO_2 fertilization feedback appears to determine the balancing of the past and present carbon budgets and dominates the temperature related feedbacks;
 - * sensitivity experiments show that the carbon balance in the model can be obtained in numerous ways, resulting in considerably different atmospheric CO_2 projections.
- These results were obtained via simulation experiments with the coupled carbon cycle/climate model, which includes the effects of biogeochemical and geophysical feedbacks, and thus this can be seen as a synergic effect of the integrated modelling approach, which could not have been achieved without coupling the models.

Simulation experiments with the methane model enable the uncertainties of the sources and sinks to be assessed, and furthermore possibilities of stabilizing the methane concentrations to be evaluated. The model is a box model that simulates globally-averaged atmospheric concentrations of methane, carbon monoxide and hydroxyl radicals, taking into account the heterogeneity of the chemical and transport processes using suitably globally-averaged descriptions of these processes involved in the CH_4 -CO-OH cycle. This straightforward approach is basically derived from of the one, two and three dimensional photochemical models. Although the methane box model is an oversimplification of complex reality, it can be used to gain more insight into the driving forces of the CH_4 -CO-OH cycle as well as to present estimates of possible future changes in chemical composition and temperatures in the atmosphere. Simulation experiments with the methane model show that:

- * in order to stabilize the atmospheric methane concentration, we do not need to know precisely the individual emissions from each anthropogenic source nor the exact changing pattern of the sources and sinks, but only the extent to which emissions exceed the capacity of the atmosphere, and how the emissions might be reduced;
- * global methane emission reductions up to 20% achieves stabilization of the atmospheric methane concentration;

- * an adequate level of emissions reductions for stabilization of the atmospheric methane concentration can be achieved from some combination of emission reductions on the different methane sources;
- * the CH_4 emission reduction requirement very much depends on the controls on other atmospheric constituents in the CH_4 -CO-OH cycle, which play a role in the methane oxidation process, especially carbon monoxide as well as nitrogen oxides and halocarbons;
- * If temperature related biogeochemical feedbacks would induce additional methane emissions the gains from the above-mentioned global emission reduction would be in danger of being offset.

An uncertainty analysis was applied to the carbon cycle model and the halocarbon model, as well to as the entire IMAGE model, in order to study the accumulation of the uncertainties in the model outcomes. The analysis focuses on the calculation and evaluation of: (i) the total uncertainty in the model outcome due to the uncertainties in the selected model parameters, and (ii) the contribution of the individual model parameters and interacting model parameters to the total uncertainty. The analysis makes use of the software package UNCSAM, which is based on Monte Carlo techniques in combination with linear regression and correlation analysis. In situations in which a linear regression models yields an inadequate fit for calculating the contribution of model parameters to the total uncertainty (see (ii)), the technique of metamodeling was applied in combination with Monte Carlo sampling. The latter was applied for the analysis of the carbon cycle model. The uncertainty analysis of the carbon cycle shows the following:

- * the terrestrial feedback processes, and especially CO_2 fertilization effect, contribute significantly to the total uncertainty in the atmospheric CO_2 concentration;
- * in general, the terrestrial parameters dominate the ocean parameters in their individual contribution to the total uncertainty;
- * interacting model parameters do not significantly contribute to the total uncertainty of the atmospheric CO_2 concentration;

- * the uncertainty bands pertaining to the atmospheric CO₂ concentration projections of IPCC-1990 Business-as-Usual (BaU90) and Accelerated Policies (AP90) scenario overlap up to 2050;
- * the relative uncertainty, defined as the deviation of the 2.5 and 97.5% percentiles from the mean value, increases in time, up to about 10-15% in the final year of simulation, 2100.

The above results refer to 'step 1', namely the emissions of greenhouse gases arriving in the atmosphere. The analysis of the entire IMAGE model shows, given that in the links in the cause-effect chain of climate change, we have the emissions of greenhouse gases to the increased atmospheric concentrations of greenhouse gases (step 1), the effects of these on the radiative forcing (step 2), and finally the effect of the latter on the globally-averaged temperature increase (step 3), that:

- * for the BaU90 scenario the relative uncertainty in 2100 increases due to cumulation of the uncertainties over these three steps. The relative uncertainty were found to be as follows: approx. 10-15% for CO₂, approx. 10-15% for CFC-11 and 5% for CFC-12 (step 1) (the uncertainty factors for the other gases were taken into account in steps 2 and 3, but their relative uncertainties have not yet been satisfactorily calculated for step 1). The level of relative uncertainty in estimating radiative forcing was approx. 10-15% (step 2), and for temperature increase about 50% (step 3);
- * the AP90 scenario yields similar results: the relative uncertainty in 2100 increases up to approx. 10-15% for CO₂, about 30-35% for CFC-11, and about 10-12% for CFC-12 (step 1), up to approx. 15-25% for radiative forcing (step 2), and for temperature increase about 55% (step 3);
- * the main uncertainties can be traced to the third step, namely due to the uncertainties in the climate sensitivity parameter ([1.5,4.5] °C), reflecting our inadequate knowledge of the geophysical feedback processes, such as cloud feedback, water vapour feedback and snow-ice albedo feedback;

- * the uncertainty bands for the temperature increase projections of the IPCC-1990 Business-as-Usual and Accelerated Policies scenarios now overlap across the entire 21st century.

Ozone depletion

The cause-effect chain of the ozone depletion problem, from the production of halocarbons, halocarbon emissions to the increased atmospheric concentrations of halocarbons (step 1), and subsequently from this to the rise in atmospheric chlorine concentration (step 2), and from there to stratospheric ozone depletion (step 3). The main scientific uncertainties can be traced to the third step. However, these uncertainties cannot be assessed using the UV-B chain model, since the stratospheric ozone depleting process also depends on a multitude of other factors (such as sulphate emissions from volcanic eruptions), which are not taken into account in the model.

The uncertainty analysis of the halocarbon model (step 1 and 2) using UNCSAM shows:

- * for the Montreal Protocol the relative uncertainty in 2100 due to cumulation of the uncertainties associated with these two steps is namely: approx. 10-15% for CFC-11, and 5% for CFC-12 in step 1 (the uncertainty factors for the other halocarbons were taken into account in step 2, but their relative uncertainties have not yet been satisfactorily calculated for step 1), up to approx. 3-5% for the atmospheric chlorine concentration in step 2;
- * for the London Amendments the relative uncertainty becomes about 30-35% for CFC-11, and about 10-12% for CFC-12, up to a factor of approx. 8-10% for the atmospheric chlorine concentration;
- * the uncertainty bands for atmospheric chlorine concentration envisaged for the Montreal Protocol and the London Amendments no longer coincide the year 2000;
- * the main uncertainties in the future atmospheric chlorine concentration (main driving force behind observed ozone

depletion) are associated with from the uncertainty in the atmospheric lifetime of CFC-11 and CFC-12.

Risk assessment: a target-oriented approach

A risk assessment approach was applied which recognises the limits of current scientific certainties in the field of the global environmental problems which are here addressed, and their possible impacts. This methodology involves assessing projected risks of various climate and ozone scenarios by coupling these scenarios with long-term targets (specific levels of a chosen environmental indicator). In the present context, a policy is associated with high risks if the chosen indicator exceeds the target value in the longer term, whereas in the case of a policy which meets the target, the anticipated risks tend to acceptable levels. Here the climate change indicators considered include the rates and magnitudes of temperature increase and sea level rise, but also the socio-economic effects of a specific case, i.e. the flooding frequency of the Dutch coastal defence system. In the case of ozone depletion, the indicators are: atmospheric chlorine concentration and mortality risks due to skin cancer caused by increased UV-B radiation induced by stratospheric ozone depletion. In addition, the methodology can be applied to the development of preventive strategies which meet the targets, and thus limit the impacts and risks inherent in the global environmental problems to a tolerable minimum (risk-minimization approach).

Climate change

The risk assessment approach has been applied in order to evaluate the future climate risks of the IPCC scenarios, using the climate change targets as formulated by the AGGG. The AGGG recommended a maximum rate of global mean temperature increase of 0.1 °C per decade, together with a maximum global mean temperature increase of 2 °C above pre-industrial global mean temperature. These temperature targets can be viewed as upper limits beyond which the

risks of considerable damages to ecosystems and sensitive coastal areas are expected to increase rapidly. In a similar manner, AGGG sets out provisional limits for the rates and magnitude of sea-level rise to prevent damage to coastal areas, wetlands and coral reefs, namely: a 2-5 cm rise in sea-level per decade and a maximum sea-level rise of between 0.2 and 0.5 m above the 1990 global mean sea-level. A difficulty with all of these targets is that they must be periodically reviewed in the light of feedbacks and non-linearities that may introduce surprises and unexpected changes. Another problem with these targets is that they are global, while large regional variation in temperature and sea-level rise are apparent. This underscores the fact that an urgent need for regionally-based targets exists, although, given the fundamental lacunae in our knowledge about regional effects of climate change, such regional targets are not yet available, and in the calculations the targets as formulated by the AGGG are used.

The risk assessment calculations using the IMAGE model show that:

- * for all IPCC-1992 scenarios and the IPCC-1990 scenarios (except the IPCC-1990 Accelerated Policies scenario) the rate and level of global temperature and sea level rise go far beyond the target levels for temperature and sea-level as identified by the AGGG, and might all be interpreted as maximum climate risk scenarios;
- * even the IPCC-1990 Accelerated Policies scenario might be considered as a moderate climate risk scenario for the next fifty years;
- * acceptance of future temperature increase implies a risk of the target rate being exceeded during the next 20 years;
- * only the here introduced alternative scenario, the Low-Risk scenario, shows that after 2010 the Low-Risk scenario outcomes for temperature and sea-level do not go beyond the AGGG defined targets.

Main characteristics of the Low-Risk scenario are a global implementation of CO₂-emission reductions of 20% in 2005 and 50% in 2025 according to the Toronto recommendations, a 20% reduction of global methane emissions, a full phase-out of CFCs by 2000 (London Amendments) and maxi-

mum control of emissions of nitrous oxide (30% reduction of anthropogenic sources). The feasibility of such a scenario, which would require a major rapid change in the global energy system towards maximum energy efficiency and the application of CO₂-free technology, is extremely doubtful.

In order to assess the socio-economic impact of a sea-level rise for the Netherlands, IMAGE (experimental version 1.6) contains a separate socio-economic impact model. The model represents a simplification of the complicated mechanisms in the fields of coastal defence and water management, and is designed to yield rough estimates. The model calculations presented here focus on the sea-level rise induced changes affecting safety, defined here as the frequency of seawater overflowing the flood protection system. The simulated estimates are compared to the present 1990 safety level, the 'Deltanorm' (equal to 0.0001 for Central Holland, i.e. a theoretical risk of inundation once every 10,000 years), and suggest that:

- * the frequency of inundation will increase with a factor eight compared to the Delta Norm according to the IPCC-1990 Accelerated Policies scenario at the end of the 21st century;
- * according to the IPCC-1990 Business-as-Usual scenario the frequency will increase by a factor as great as thirty, and tends to match the statistical chance of inundation on a scale comparable to the disastrous storm surge in 1953;
- * to counteract these increased risks, the Dutch dikes should be raised before 2000, otherwise the risks facing the population will be far exceed the 'Delta Norm'.

As argued above, if major climate risks are to be avoided, a worldwide reduction in the emissions of greenhouse gases is required. In order to develop an effective international response to climate change, which recognizes the present and historical iniquities between developing and industrialized countries, an approach for the allocation of the CO₂ emission reductions among regions is presented, which is based on an equity rule, by which all past and future inhabitants on

the Earth are permitted to emit an equal CO₂ quatum per year.

The results of the calculations for the IPCC-1990 Accelerated Policies Scenario show that:

- * the EC and North America have built up an emission debt of 36 GtC and 75 GtC resp. given recent World Bank projections of population growth;
- * the developing countries, however, have built up an emission credit of 24 GtC;
- * these regional emission debts and credits increase the future per capita budget for the developing regions up to 0.2-0.8 tC/cap annually, whereas North America and the EC end up with a negative future carbon budget of 0.4 to 1.5 tC/cap annually;
- * Even according to the IPCC Business-as-Usual scenario, the future emission quota of most industrialized countries will be lower than their present per capita emissions, e.g. North America would have a negative annual future carbon budget of 0.3 tC/cap.

Ozone depletion

Here the risk assessment approach has been applied in order to evaluate a wide range of halocarbon production scenarios, using the ozone targets as formulated by the WMO, and based on model calculations with the halocarbon model. This model, as part of the UV-B chain model, simulates halocarbon concentrations, and the resulting atmospheric chlorine concentration and radiative effects due to the halocarbons. The model has the following characteristics: (i) the production and consumption of halocarbons is disaggregated into nine regions and five end-use categories; (ii) the model includes five CFCs, carbon tetrachloride, methylchloroform, HCFC-22, three imaginary substitutes (representing a class of alternatives), two halons, CH₃Cl and CH₃Br; (iii) the time-delayed emissions depend on the end-use category; (iv) the direct radiative forcing and atmospheric concentration relationships are incorporated; (v) the indirect radiative effects of halocarbons associated with the radiative effects of stratospheric ozone depletion are incorporated.

The ozone targets adopted by the WMO are the following: the first ozone target is the atmospheric chlorine concentration level of 3 ppbv (the chlorine abundance which obtained in the mid-1980s when the first signs of ozone depletion were observed at middle latitudes in spring and summer), beyond which level maximum ozone risks occur. The second ozone target is the chlorine level of 2 ppbv (the chlorine abundance in the late 1970s when the Antarctic ozone hole as well as the accelerated trends in the total ozone column in the Northern Hemisphere were first observed), beyond which level high ozone risks occur. The 2 ppbv-level is internationally seen as the 'no-effect' level, and as a possible sustainable target.

The risks assessment calculations run on the halocarbon model show for the present protocols that:

- * even a full implementation of the Copenhagen Amendments induces maximum ozone risks (chlorine concentration above the 3 ppbv level) until around 2020, and high ozone risks (chlorine concentration above the 2 ppbv level) until around 2060;
- * for the London Amendments these goals are not achieved until around 2040 and 2070, respectively;
- * the atmospheric chlorine loading will peak for both policies around 2000, and at that time the highest ozone losses are expected. However, this study also examines a number of currently feasible, more pessimistic, developments in halocarbon production, which affects the duration of the time period with associated maximum/high ozone risks:
- * stabilization/growth of the production of long-life CFCs in the non-complying countries (mainly the developing world) results in maximum ozone risks for the entire 21st century;
- * partial compliance with the London Amendments: less than 90% compliance in itself implies maximum/high ozone risks for the entire 21st century;
- * delayed scheduling of the world-wide phase-out of the currently-regulated halocarbons to approximately the year 2010: maximum ozone risks until 2050 with a peak of chlorine loading which is 10%

higher than the peak value envisaged in the London Amendments;

- * delayed phase-out to the year 2040 in the developing world: maximum ozone risks until approximately 2050, with ozone risks remaining high until approximately the year 2090.

However, negative ozone implications might also be expected to result from the increasing use of HCFC-22 or similar compounds as substitutes for the phased-out CFCs (currently regulated in the Copenhagen Amendments), as shown by:

- * increasing production of HCFC-22; maximum ozone risks remain until around 2070, after which they are still high;
- * increasing production of the HCFCs after the substitution process leads to maximum ozone risks up to the year 2050, and afterwards high ozone risks.

With respect to the climate risks, special attention should be paid to the HFCs (zero Ozone Depletion Potential) with long atmospheric lifetimes and a relatively high Global Warming Potential.

- * increasing production of these HFCs does, however, result in moderate halocarbon-climate risks after approximately the year 2050.

In order to assess the future risks of skin cancer due to ozone depletion for the Netherlands, simulation experiments have been conducted with the UV-B chain model (coupled halocarbon/UV-B impact model). This integrated model considers the entire cause-effect chain of ozone depletion problem, from the production of halocarbons, the emission thereof from households and landfill sites, the changes in atmospheric concentration of CFCs (step 1) and chlorine (step 2), stratospheric ozone depletion (step 3), to the increased UV-B exposure at the Earth's surface (step 4), and finally the adverse human health effects, in terms of skin cancer risks due to ozone depletion (step 5). The halocarbon model covers steps 1 and 2, whereas the UV-B impact model covers steps 3 to 5.

The UV-B impact model treats the stratospheric ozone losses as a linear function of stratospheric chlorine concentration, which is

evidently a simplified description of the atmospheric chemistry and transport processes in the lower stratosphere. Nevertheless, model studies show indeed that the ozone budget in the lower stratosphere is mainly controlled by the evolution of the chlorine-monoxide related chemistry, and is less affected by nitrogen-oxides or bromine related chemistry. Still, it could be argued that this modelling technique is too far removed from the real world, but for the purposes of this study, it nevertheless yields useful insights into possible future changes in stratospheric ozone depletion and its impacts. The change in UV-B radiation is modelled using a regression model of an atmospheric UV-transfer model, and subsequently, the carcinogenic effective UV-dose is calculated using an action spectrum for photocarcinogenic effects, which weights the total effective spectral UV-B doses of different wavelengths. The change in incidence of skin cancer is calculated as a function of the cumulative, long-term carcinogenic effective UV-B exposure.

Although no mortality risk targets regarding skin cancer due to ozone depletion have yet been determined, the health risk target adopted here is the maximum mortality risk target for substances and sources of ionized radiation of 10^{-6} (1 per million), as recommended by the Dutch Ministry of the Environment (VROM). Such an annual mortality risk can be viewed as an upper limit beyond which health risks become unacceptable.

Simulations experiments with the UV-B chain model show that:

- * the Copenhagen Amendments lead to a peak in the atmospheric chlorine concentration by approx. 2000, in stratospheric ozone depletion by approx. 2005 (five years after the peak in chlorine), and in the effects in skin cancer by approx. 2045 (40-50 years after the peak in chlorine);
- * the latter delay is mainly due to the fact that skin cancer incidences depend on the cumulative UV-B exposure during a human lifetime, and the development of skin cancer after a period of increased UV-B radiation generally starts to manifest itself after 40-50 years;

- * the excess mortality rate due to skin cancer (defined as extra number of deaths per year associated with stratospheric ozone depletion) according to this protocol exceeds the health risk target, after 1995, peaks at about 3 times the target in 2045, and then returns to health risk target level at the end of the 21st century;
- * therefore, even this protocol is still a high health risk scenario for the whole next century;
- * the excess mortality rate due to skin cancer according to the London Amendments shows a similar pattern as that of the Copenhagen Amendments: a peak of almost 4 times the target in 2045, and a return to the target soon after the 21st century.

Sensitivity experiments with the model show that:

- * a reduction in the exposure of human skin to UV radiation due to a change of lifestyle would largely reduce the excess mortality rates, even more than an accelerated phase-out of CFCs.
- * a 40% increase in the ozone depletion rate-coefficient (leading to a 16% ozone depletion in 2000, instead of 10% in the reference case) would lead to 45-50% higher mortality rates.

Synthesis: ozone depletion and climate change

For the main indicators of the global environmental problems, temperature increase (climate change) and atmospheric chlorine concentration (ozone depletion) according to a wait-and-see policy for climate change (IPCC-1992 scenario IS92a) and a risk minimization policy for climate change (Low-Risk scenario), both policies combined with the Copenhagen Amendments for ozone depletion, are depicted in *Figure 15.1*. In this Figure the rate of temperature increase is given as a function of the chlorine level. Furthermore six climate/ ozone risk areas are also presented in this Figure. The six climate/ozone risk areas are now defined as: a maximum ozone/climate risk area (>3 ppbv and $>0.1^{\circ}\text{C}/\text{decade}$); a maximum ozone and low climate risk area (>3 ppbv and

Figure 15.1: The Wait-and-see policy and the Risk minimization policy related to the ozone and climate targets

- I maximum ozone/climate risk area (>3 ppbv and >0.1 °C/decade)
- II maximum ozone and low climate risk area (>3 ppbv and <0.1 °C/decade)
- III high ozone/climate risk area (>2 and <3 ppbv and >0.1 °C/decade)
- IV high ozone and low climate risk area (>2 and <3 ppbv and <0.1 °C/decade)
- V moderate ozone and high climate risk area (<2 ppbv and >0.1 °C/decade)
- VI low climate/ozone risk area (<2 ppbv and <0.1 °C/decade)

<0.1 °C/decade); a high ozone/climate risk area (>2 and <3 ppbv and >0.1 °C/decade); a high ozone and low climate risk area (>2 and <3 ppbv and <0.1 °C/decade); a moderate ozone and high climate risk area (<2 ppbv and >0.1 °C/decade); and a low climate/ozone risk area (<2 ppbv and <0.1 °C/decade).

The ozone risks for both scenarios are the same, because the same halocarbon production policy followed, namely: the Copenhagen Amendments. For the coming thirty years maximum ozone risks are present, and not until halfway through the 21st century is the low ozone risk area achieved. For the climate risks, the wait-and-

see policy induces high/maximum climate risks for the whole 21st century, the rate of temperature increase even exceeds the 0.3 °C per decade threshold, whereas the risk minimization view, represented by the Low-Risk scenario, leads to low to moderate climate risks in twenty years time. However, the Low-Risk scenario does reflect a maximum feasible effort towards low climate risks, the world faces the prospect of high climate risks over the next two decades, in combination with maximum ozone risks. It is a task of both social and physical scientists to clarify the gravity of the situation for decision-makers, and the tasks of model-builders to provide them with effective tools.

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Abbreviations

Acronyms: institutions/frameworks

AGGG	Advisory Group on Greenhouse gases
CBS	Central Bureau of Statistics
CPB	Central Planning Bureau
CCC	Canadian Climate Centre, Downsview, Ontario, Canada CMA Chemical Manufacturers Association
CEC	Commission of European Communities
CRU	Climatic Research Unit, University of East Anglia, UK
EPA	Environmental Protection Agency, Washington, USA
FAO	Food and Agriculture Organisation of the United Nations
GFDL	Geophysical Fluid Dynamics Laboratory, Princeton, USA
GISS	Goddard Institute for Space Studies, New York, USA
IEA	International Energy Agency, Paris, France
IIASA	International Institute for Applied Systems Analysis, Laxenburg, Austria
IMF	International Monetary Fund
INC	Intergovernmental Negotiating Committee
IPCC	International Panel on Climate Change
MPI	Max Planck Institut, FRG
NASA	National Aeronautics and Space Administration, USA
NCAR	National Center for Atmospheric Research, Boulder, USA
NOAA	National Oceanic and Atmospheric Administration, USA
OECD	Organisation for Economic Co-operation and Development
OSU	Oregon State University, USA
SCOPE	Scientific Committee on Problems of the Environment
SEI	Stockholm Environment Institute, Stockholm

RIVM	National Institute of Public Health and Environmental Protection, Bilthoven, The Netherlands
UKMO	Meteorological Office, Bracknell, UK
UN	United Nations
UNCED	United Nations Conference for Environment and Development, Rio de Janeiro, 1992
UNEP	United Nations Environment Programme
UNGA	United Nations General Assembly
VROM	Dutch Ministry of Housing, Physical Planning and Environment
USDOE	Department of the Energy, USA
WCRP	World Climate Research Programme
WMO	World Meteorological Organization
WRI	World Resources Institute

General

AP90	IPCC-1990 Accelerated Policies scenario
ASF	Atmospheric Stabilization Framework
BaU90	IPCC-1990 Business-as-Usual scenario
CP90	IPCC-1990 Control Policies scenario
EBM	Energy Balance Model
ESCAPE	the Evaluation of Strategies to address Climate change by Adapting to and Preventing Emissions
GCM	General Circulation Model
GPP	Gross Primary Production
GWP	Global Warming Potential
IMAGE	an Integrated Model to Assess the Greenhouse Effect
IS92a-f	IPCC-1992 scenarios a-f
Low90	IPCC-1990 Low Emissions scenario
NH	Northern Hemisphere
NP	Net Photosynthesis
NPP	Net Primary Production
ODP	Ozone Depletion Potential
RCM	Radiative Convective Model

SH	Southern Hemisphere
TOMS	Total Ozone Mapping Spectrometer
UNCSAM	UNCertainty analysis by Monte Carlo SAMpling techniques
UV	ultraviolet radiation

Units

°C	degrees Celsius
Dfl	Dutch florins or guilders
Gt	gigatons (10^{15} gram)
GtC	gigatons of carbon
K	degrees Kelvin
kg	kilogram
km	kilometer
λ	lambda
m	meter
Mha	Million of hectares
Mkg	Million kilogram (10^9 gram)
mole	mol
ppmv	parts per million (10^6) by volume
ppbv	parts per billion (10^9) by volume
pptv	parts per trillion (10^{12}) by volume
s	second
Tg	Teragram (10^{12} gram)
Wm ⁻²	watts per meter square

CBrF ₃	halon-1301
CH ₃ Br	methyl bromide
CO	carbon monoxide
CO ₂	carbon dioxide
CH ₃ Cl	methyl chloride
CH ₃ Br	methyl bromide
CH ₄	methane
Cl	chlorine
H	hydrogen
H ₂ O	water
N	atomic nitrogen
N ₂	molecular nitrogen
N ₂ O	nitrous oxide
NMHC	nonmethane hydrocarbons
NO	nitric oxide
O ₃	ozone
OH	hydroxyl
O	atomic oxygen
O ₂	molecular oxygen
SO ₂	sulphur dioxide

Chemical symbols

Br	bromine
CCl ₄	carbon tetrachloride
CFC-11	CCl ₃ F
CFC-12	CCl ₂ F ₂
CFC-113	C ₂ Cl ₃ F ₃
CFC-114	C ₂ Cl ₂ F ₄
CFC-115	C ₂ ClF ₅
CH ₃ CCl ₃	methylchloroform
CHCl ₃	chloroform
CHClF ₂	HCFC-22
C ₂ HCl ₂ F ₃	HCFC-123
C ₂ HClF ₄	HCFC-124
C ₂ HF ₅	HFC-125
C ₂ H ₂ F ₄	HFC-134a
C ₂ H ₃ Cl ₂ F	HCFC-141b
C ₂ H ₃ ClF ₂	HCFC-142b
C ₂ H ₃ F ₃	HFC-143a
C ₂ H ₄ F ₂	HFC-152a
C ₃ HCl ₂ F ₅	HCFC-225a
C ₃ HCl ₂ F ₄	HCFC-225cb
CBrClF ₂	halon-1211

Samenvatting

De laatste jaren staan de grootschalige milieuproblemen klimaatverandering en ozonaantasting in het brandpunt van de belangstelling, zowel wetenschappelijk als beleidsmatig. Daarmee groeit ook de behoefte aan instrumenten die zowel beleidsmakers als wetenschappers helderheid verschaffen ten aanzien van de complexe klimaat- en ozonproblematiek. Dit proefschrift beschrijft een geïntegreerd, beleidswetenschappelijk simulatiemodel waarmee lange-termijn klimaat- en ozonstrategieën kunnen worden ontwikkeld en geëvalueerd. Dit model is een experimentele versie van het computersimulatiemodel IMAGE, an Integrated Model to Assess the Greenhouse Effect (hierna: IMAGE (experimentele versie 1.6)), bestaande uit de belangrijkste modules van IMAGE (versie 1.6), en het UV-keten model. Beide modellen zijn op het Rijksinstituut voor Volksgezondheid en Milieuhygiëne (RIVM) ontwikkeld teneinde een overzicht te geven van de mechanismen en de oorzaak-effectrelaties met betrekking tot het klimaat- en ozonprobleem. In dit proefschrift wordt het IMAGE model gebruikt om: (1) de onzekerheden of leemtes in de huidige kennis omtrent beide mondiale milieuproblemen te identificeren en te analyseren; (2) diverse lange-termijn klimaat- en ozonstrategieën te evalueren in termen van toekomstige potentiële risico's voor het klimaat en de ozonlaag, alsmede preventieve strategieën te ontwikkelen, teneinde de toekomstige risico's te reduceren tot aanvaardbare waarden.

Dit proefschrift is als volgt opgebouwd. Deel I geeft na een inleiding op de doelstellingen en de methodologie van dit onderzoek (hoofdstuk 1), een kort overzicht van de mondiale milieuproblemen klimaatverandering en ozonaantasting (hoofdstuk 2). In deel II (hoofdstuk 3) wordt het simulatiemodel IMAGE (experimentele versie 1.6) beschreven.

Deel III (hoofdstukken 4-8) beschrijft een aantal studies, waarin geïllustreerd wordt hoe een dergelijk model gebruikt kan worden ten einde de diverse onzekerheden of leemtes in de huidige kennis te analyseren en te evalueren (doelstelling (1)). Hoofdstuk 4 behandelt in het kort de voornaamste huidige onzekerheden in het klimaat- en ozonprobleem, en beschrijft vervolgens de gebruikte methodologie van deel III, zoals: gevoeligheids- en onzekerheidsanalyse. In hoofdstuk 5 worden de IPCC-1990 en IPCC-1992 scenarios besproken, welke in de verdere analyses met het model worden gebruikt. In Hoofdstuk 6 wordt de kwantitatieve rol van een aantal terugkoppelingsprocessen in de koolstofcyclus geëvalueerd. Hiervoor wordt een aantal biogeochemische terugkoppelingen, welke momenteel redelijkerwijs kunnen worden gekwantificeerd, ingebouwd in het koolstofcyclusmodel, als onderdeel van IMAGE, en vervolgens worden een groot aantal modelsimulaties uitgevoerd. Uitgangspunt hierbij is deze terugkoppelingen in het model te gebruiken om het huidige en vroegere koolstofbudget in balans te krijgen. Dit alles leidt uiteindelijk tot schattingen van het toekomstige CO₂-concentratie, welke aanzienlijk lager zijn dan de recente schattingen van de IPCC: voor het IPCC-1990 'Business-as-Usual' scenario is het verschil 16% ten aanzien van het 1990-niveau. Hoofdstuk 7 presenteert, na een inventarisatie van de onzekerheden in de bronnen en putten van methaan, een serie modelberekeningen met het methaanmodel van IMAGE. De berekeningen tonen aan dat een 20% reductie van methaan emissies kan leiden tot een stabilisatie van de atmosferische methaan concentraties op het huidige niveau. De vereiste reductie van de methaan emissies hangt sterk af van het toekomstige beleid ten aanzien van de andere gasen binnen de CH₄-CO-OH cyclus, zoals koolmonoxide, NO_x en de CFK's. Hoofdstuk 8 beschrijft een onzekerheidsanalyse op het koolstofcyclusmodel, op het CFK model, en op het gehele IMAGE model. Hiervoor is gebruik gemaakt van het software pakket UNCSAM, en de techniek van metamodellering in combinatie met Monte Carlo sampling. Getoond wordt dat, gaandeweg de keten van het klimaatprobleem doorlopend van de emissies, de veranderingen

in concentraties van broeikasgassen, veranderingen in de stralingshuishouding, en uiteindelijk de temperatuurstijging, treedt er een accumulatie op van de onzekerheden. De relatieve onzekerheden, gedefinieerd als de afwijking van de 2.5% en 97.5% percentielen tot de gemiddelde waarden, bedragen voor het IPCC-1990 'Business-as-Usual' scenario in het jaar 2100, 10-15%, 10-15% en 5% voor de atmosferische concentratie van CO₂, CFK-11 en CFK-12, respectievelijk, en 10-15% voor de verandering in stralingshouding, en uiteindelijk ongeveer 50% voor de temperatuurstijging.

In deel IV (hoofdstukken 9-14) wordt een risico-benadering beschreven, waarin het model IMAGE is gebruikt om de model-uitkomsten van de diverse emissie-scenario's te relateren aan duurzaamheidsnormen, zoals deze zijn geformuleerd voor het klimaatprobleem door de AGGG, en voor het ozonprobleem door de WMO. Deze methodologie van risico-evaluatie wordt beschreven in hoofdstuk 9. Hoofdstuk 10 geeft een gedetailleerde beschrijving van het CFK model, als onderdeel van het UV keten model. Met dit model worden een aantal emissie scenario's voor de CFK's als ook de HCFK's en HFK's (de 'zachte' CFK's) geëvalueerd in termen van toekomstige ozon-risico's. De berekeningen tonen aan dat zelfs bij een volledige implementatie van het huidige CFK-beleid, zoals vastgelegd in de Kopenhagen 'Amendments' van het Montreal Protocol, hoge tot maximale ozon-risicogehaltes voor de komende dertig tot veertig jaren niet te vermijden zijn. Pas in de tweede helft van de volgende eeuw bereikt de atmosferische chloride concentratie het niveau van eind jaren zeventig, wanneer het 'ozongat' voor het eerst voorkwam. In hoofdstuk 11 worden berekeningen gepresenteerd met het IMAGE-model, welke aantonen dat de snelheid en het niveau van temperatuurstijgingen als uitkomst van de vier IPCC-1990 scenario's de gestelde klimaatdoelstellingen of duurzaamheidsnormen, in ruime mate overschrijden. In termen van risico's voor het klimaat kan het IPCC-1990 'Business-as-Usual' scenario worden beschouwd als een maximaal klimaat risicoscenario. Zelfs het meest vergaande scenario het IPCC-1990 'Accelerated Policies' scenario, brengt een zeker risico met zich mee. 'Delayed response'-berekeningen met IMAGE laten voorts zien dat, door vertragen en terugkoppelingen in het fysisch/chemisch processen, het tijdstip waarop internationale maatregelen worden genomen om CO₂-emissiereducties te bewerkstelligen van cruciaal belang is, en dat een snelle initiatie van internationaal klimaatbeleid noodzakelijk is. Hoofdstuk 12 beschrijft een modelstudie naar de invloed van een zeespiegelstijging op de kustverdediging van Nederland. Getoond wordt dat wanneer er geen dijkverzwaringen plaats vinden, de toekomstige overschrijdingsfrequentie het niveau van de Deltanorm aanzienlijk zal overschrijden. Hoofdstuk 13 bevat een beschrijving van het UV impact model (onderdeel van het UV keten model). Berekeningen met het UV keten model tonen aan dat bij een volledige implementatie van Kopenhagen Amendments, de ozonaantastingen maximaal zullen zijn rond het jaar 2000, en de effecten in termen van verhoogde incidenties van huidkanker als gevolg van de extra UV-B straling door de ozonafnames maximaal zijn rond 2040. Deze vertragingperiode van 40 tot 50 jaar komt overeen met de gemiddelde tijdsduur voor de ontwikkeling van huidkanker. Zelfs voor dit scenario wordt de tentatieve grenswaarde van één dode per miljoen, als het maximaal toelaatbare aantal extra jaarlijkse sterftegevallen aan huidkanker tengevolge van de extra UV straling door ozonaantasting, voor de gehele komende eeuw overschreden. In hoofdstuk 14 wordt een methodologie beschreven voor de allocatie van CO₂ emissiereducties voor de verschillende wereld regio's. Deze methodologie is gebaseerd op het gelijkheidscriterium: ieder mens op aarde, zowel in het verleden, heden, als in de toekomst, recht heeft op eenzelfde hoeveelheid CO₂-emissie per jaar. De resultaten van de berekeningen voor het IPCC-1990 'Accelerated Policies' scenario geven aan, dat de EG en de Verenigde Staten op grond van hun historische CO₂-emissies een emissie schuld hebben opgebouwd van respectievelijk 35 en 75 GtC, en tevens, dat deze regio's hun toekomstige emissierechten al volledig hebben verbruikt. Daarentegen hebben de ontwikkelingslanden een totaal emissiekrediet van 24 GtC opgebouwd, resulterend in toekomstige jaarlijkse emissierechten van 0.2 tot 0.8 ton C per inwoner.

In deel V (hoofdstuk 15) tenslotte, worden de bevindingen uit het onderhevige proefschrift samengevat en geëvalueerd.

Curriculum vitae

Michel den Elzen werd geboren op 1 augustus 1965 te Ter Aar. In 1984 behaalde hij het diploma VWO aan het Alkwin Kollege te Uithoorn. Van 1984 tot 1989 studeerde hij Wiskunde aan de Vrije Universiteit te Amsterdam. In het kader van zijn afstudeerstage werd gedurende de periode april tot december 1988 stage gelopen bij het Rijksinstituut voor Volksgezondheid en Milieuhygiëne (RIVM). Bij het Centrum voor Wiskundige Methoden (CWM) werd een simulatiemodel ontwikkeld voor de kwantificering naar de sociaal-economische gevolgen van klimaatsveranderingen voor Nederland, welke een deelmodel vormt voor het geïntegreerd klimaatsmodel IMAGE. In februari 1989 studeerde hij af met als hoofdrichting Wiskunde, Statistiek en Operations Research. In dezelfde maand volgde een aanstelling als Assistent in Opleiding (AIO) bij de vakgroep Wiskunde van de Rijksuniversiteit Limburg volgde met als promotieonderzoek Operations Research en global mileuproblemen. Per 1 maart 1990 trad hij in dienst bij de afdeling CWM van het RIVM als wetenschappelijk medewerker Operations Research. Bij deze afdeling werd een groot deel van het promotieonderzoek verricht. Sinds januari 1992 is hij werkzaam binnen het project 'Global Dynamics and Sustainable Development'. De voornaamste doelstelling van dit project is het begrip duurzame ontwikkeling op mondiale schaal te operationaliseren. Teneinde een overzicht te geven van de oorzaak-effect relaties tussen sociale en economische processen, biofysische processen en uiteindelijk de effecten op ecosystemen en de mens, wordt een geïntegreerd simulatiemodel ontwikkeld: TARGETS (a Tool to Assess Regional and Global Environmental and health Targets for Sustainability).