AN INTEGRATED MODEL FOR THE ASSESSMENT OF THE GREENHOUSE EFFECT: THE DUTCH APPROACH

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Abstract. This paper describes a simulation policy model of the combined greenhouse effects of trace gases. With this model, the Integrated Model for the Assessment of the Greenhouse Effect (IMAGE) scenarios for the future impact of the greenhouse effect can be made, based on different assumptions for technological and socio-economic developments. The contribution of each trace gas can be estimated separately.

Basically the model, consisting of a number of coupled modules, gives policy makers a concise overview of the problem and enables them to evaluate the impact of different strategies. Because the model covers the complete cause-effect relationship it can be utilized to derive allowable emission rates for the different trace gases from set effect related targets. Regular demonstration sessions with the simulation model have proven the importance of such science based integrated models for policy development.

Four different scenarios are worked out for the most important trace gases (CO_2, CH_4, N_2O, CFC-11 and CFC-12). One of these scenarios can be regarded as a growth scenario unrestricted by environmental concerns. The others are based on different strategic policies. After the simulation of future trace gas concentrations global equilibrium temperature increases are computed. Finally the sea level rise, the most threatening effect of the greenhouse problem for the Netherlands, is estimated.

Simulation results so far emphasize the importance of trace gases other than CO_2. The Montreal Protocol on reduction of CFC is found to stabilize the relative contribution of these substances to the greenhouse effect.

Introduction

Until recently the greenhouse problem was primarily attributed to the emission of CO_2 resulting from the combustion of fossil fuel. At the Villach Conference in 1985 the role of other trace gases was considered to be equally important, advancing the data the GCM show for doubled atmospheric concentration of CO_2. To policy makers the relation to various issues such as economic development, changes in biogeochemical cycles (especially that of carbon), the melting of ice caps and sea level rise is not always clear. Many of these topics are dealt with in independent studies. An integration of knowledge is needed to answer practical 'what if' questions.

As a reference institute of the Dutch government, RIVM has therefore developed a simulation model of the greenhouse problem. The primary objective of this model is threefold: firstly to offer policy agencies a concise overview of the quantitative aspects of the greenhouse problem, secondly to identify uncertainties or cru-

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cial gaps in current knowledge, and thirdly to calculate the effects of several policy options concerning the greenhouse problem. In the long run it is meant to be an interactive tool for policy makers.

The model is not yet complete, but is continually updated, improved and extended. In this paper the results of the first project phase are presented. The feasibility of a policy oriented model based on scientific principles and consisting of a combination of modules has been investigated. Demonstrations given for high level Dutch policy officials and in Parliament have proven the model to be a helpful tool to improve the understanding of the greenhouse problem.

Model Description

The model is based on a large variety of data derived from both an extensive study of literature and knowledge transfer resulting from consultations of specialized experts. In this way the problem could be dealt with by combining different fields of research. The integrated information in the model yields insights which cannot be obtained from scattered information.

We modelled the greenhouse problem as a dynamic system with discrete time steps of one year and a simulation time of 200 yr, from 1900 to 2100. The system has a global character, entailing absence of spatial dimensions. The components (modules) of the model are given in Figure 1, in which an arrow from one component to another represents a driving influence from the first component to the second. The associated computer model, the Integrated Model for the Assessment of the Greenhouse Effect (IMAGE), consists of independent modules which are linked together, the modular structure allowing improvements to be implemented gradually without affecting the basic structure.

The framework of IMAGE consists of emission modules, a concentration module, a module converting concentration increases into temperature rise and finally modules deriving the sea level rise from temperature changes. The modules are linked in a simple way: the output of one module serves as input for the next. The modules mentioned are highly aggregated with a dynamic structure. The model, excluding the energy module, contains some 1500 equations, of which approximately 400 are for the carbon cyle.

At present the model includes five trace gases: CO_2, CH_4, N_2O, CFC-11 and CFC-12. In the emission modules current estimates of historical emissions are implemented for the period 1900 to 1985. For the period 1985 to 2100 four sets of scenarios were chosen. An emission scenario is defined as a possible future development, without pretending probability being a prediction. Furthermore, we define a set of scenarios as a similar, consistent development for all trace gases. The underlying scenario assumptions, which will be discussed in more detail later, are based on a study of the sources of trace gas emissions: the anthropogenic sources being primarily energy supply, agriculture and industry. The module is run with global, annual emission figures (see Figures 2, 3, 4 and 5).

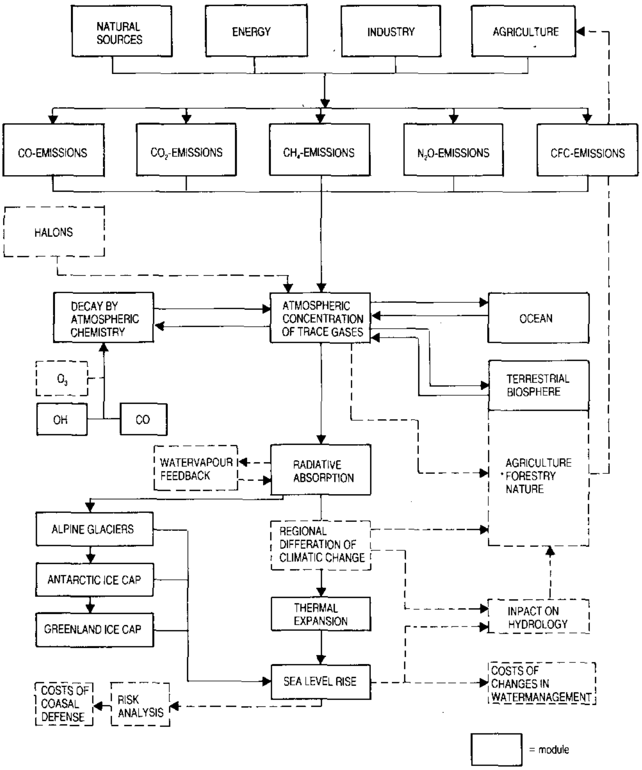

Fig. 1. Extended integrated model for the assessment of the greenhouse effect.

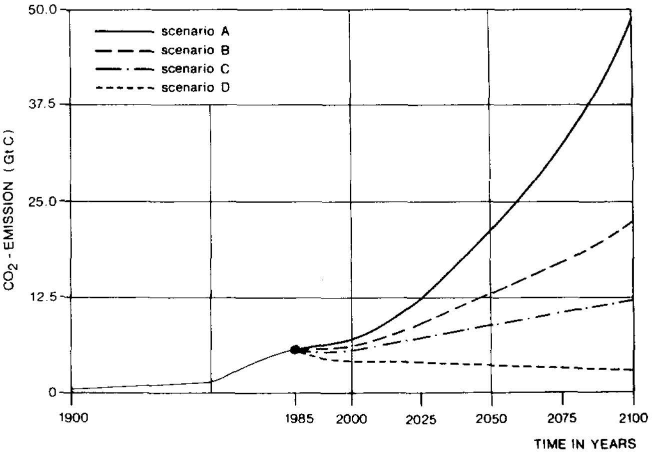

Fig. 2. Emisison of CO_2.

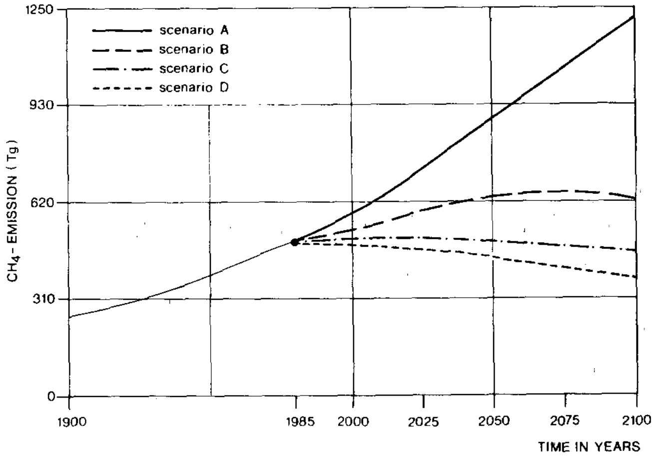

Fig. 3. Emission of CH_4.

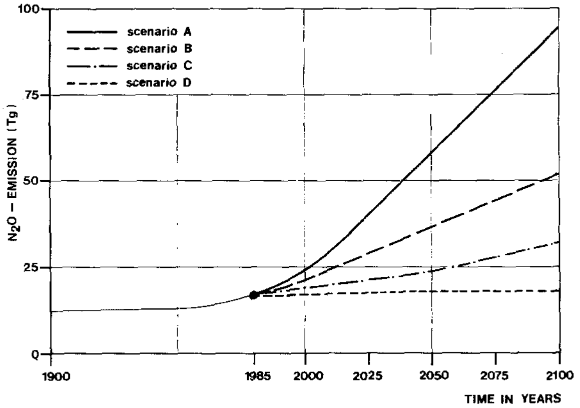

Fig. 4. Emission of N_2O.

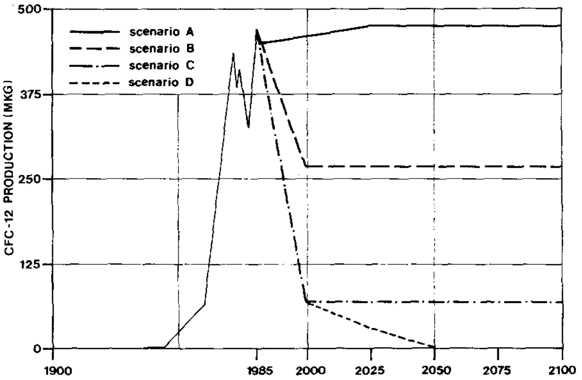

Fig. 5. Production of CFC-12.

The emission modules provide the input for the concentration module. The emission and concentration of CO_2 is linked to an ocean module and a terrestrial biota module, together reflecting the C-cycle. The latter has been modelled according to Goudriaan and Ketner (1984). As a consequence of the coupling of the emission-, concentration- and terrestrial biota modules the airborne fraction has been defined in a specific sense: the airborne fraction is the fraction of the total CO_2-emissions from fossil fuels and biosphere changes that remains in the atmosphere. In formula:

$$Af = \frac{\text{net increase of } CO_2 \text{ in the atmosphere}}{\text{fossil fuel emission} - \text{net terrestrial biota uptake}} \tag{1}$$

$$= \frac{fsem - \Delta ocean + bioem - bioupt}{fsem + bioem - bioupt} = \frac{fsem - \Delta ocean - \Delta biota}{fsem - \Delta biota}$$

with

Af = airborne fraction
$fsem$ = fossil fuel emission
$\Delta ocean$ = CO_2-uptake by the ocean
$\Delta biota$ = net biota uptake = $bioupt - bioem$
$bioem$ = emission released from terrestrial biota by human disturbance
$bioupt$ = uptake by terrestrial biota, equivalent with the total net ecosystem production.

The modular structure for the other trace gases is quite different from that of CO_2. The removal of the trace gases concerned by atmospheric chemical processes is an essential feature. Spatial dimension of the simulated trace gas concentration is zero. Generally, the trace gas concentrations of CH_4, CO, N_2O, CFC-11 and CFC-12 are expressed as

$$pX(t) = pX(t-1) + \int_{t-1}^{t} (convfX^{*}emX(\tau) - remvlX^{*}pX(\tau-\Delta\tau))d\tau\,, \tag{2}$$

with

$pX(t)$ = tropospheric concentration of a trace gas at time t (in ppb)
$emX(t)$ = global emission of a trace gas at time t (in Tgy^{-1})
$convfX$ = conversion factor of trace gas X (in $ppbTg^{-1}$)
$remvlX$ = removal rate of trace gas X (in y^{-1}).

The concentration of methane is derived from the global CH_4-CO-OH cycle by simulating the main atmospheric chemical prosesses influencing the global concentrations of these trace gases. The removal rates of CH_4 and CO are determined by the uptake-, transport- and oxidation rates of these trace gases, the latter being dependent on the OH-concentration (Thompson and Cicerone, 1986; Khalil and Rasmussen, 1985; Brühl and Crutzen, 1988; Isaksen and Høv, 1987; Rotmans and Eggink, 1988; Swart, 1988).

For N_2O and CFC the removal rate is supposed to be inversely proportional to the atmospheric lifetime (Rotmans, 1986). For CFC production figures are the input for the emission module, taking into account the delay time between the production and emission for different fractions of CFC-uses (Miller and Mintzer, 1986).

The calculated trace gas concentrations serve as an input for the climate module. The total change in radiative forcing ΔQ_{tot}) resulting from concentration changes of CO_2, CH_4, N_2O, CFC-11 and CFC-12 is modelled according to Wigley (1987):

$$\begin{aligned}\Delta Q_{tot} = {} & 6.333^{*}\ln(pCO_2/pCO_2 in) + 0.0398^{*}(\sqrt{}CH_4 - \sqrt{}pCH_4 in) + \\ & 0.105^{*}(\sqrt{}pN_2O - \sqrt{}pN_2O in) + 0.27^{*}pCFC\text{-}11 + 0.31^{*}pCFC\text{-}12\,,\end{aligned} \tag{3}$$

with

ΔQ_{tot} = total change in radiative forcing
pCO_2, pCH_4, pN_2O, $pCFC$ = concentrations of CO_2, CH_4, N_2O and CFC
$pCO_2 in$, $pCH_4 in$, $pN_2O in$ = initial concentrations (at time = 1900).

The resulting global mean equilibrium surface temperature rise can be calculated from (3) by multiplying the radiative forcing by a climate feedback factor in which the water vapour factor is explicitly taken into account (Dickinson, 1986; Wigley, 1985; Tricot and Berger, 1987; Ramanathan, 1985; Health Council, 1983).

The effects of global warming on the potential sea level are determined by four processes: thermal expansion of ocean water, melting of alpine glaciers, and ablation or accumulation of the Greenland and Antarctica ice caps:

$$\Delta Zsp(t) = \Delta Zsp_{thex}(t) + \Delta Zsp_{glac}(t) + \Delta Zsp_{Gr}(t) + \Delta Zsp_{Ant}(t)\,, \tag{4}$$

with

$\Delta Zsp(t)$ = eustatic sea level rise at time t (in cm)
$\Delta Zsp_{thex}(t)$ = sea level rise due to thermal expansion of the ocean (in cm)
$\Delta Zsp_{glac}(t)$ = sea level rise due to melting of glaciers (in cm)
$\Delta Zsp_{Gr}(t)$ = sea level rise due to net increase of ablation of Greenland (in cm)
$\Delta Zsp_{Ant}(t)$ = sea level rise due to net increase of accumulation of Antarctica (in cm).

The information necessary for the description of the various complicated aspects of the phenomenon sea level rise is derived from Barnett (1983), Gornitz *et al.*

(1982), Meier (1984), Revelle (1983), Robin (1985), United States Department of Energy (1985), Van der Veen (1986), Barth and Titus (1984), Oerlemans (1987), and has been integrated and aggregated to a high abstraction level.

The thermal expansion effect is divided into a uniform expansion for the mixed layer (0–75 m) of the ocean module of Goudriaan and Ketner (1984) and, by differential equations, a delayed expansion effect for the layers below (75–1000 m), determined by the depth, atmospheric temperature increase, thermal expansion coefficient and a time lag of 25 yr after equilibrium temperature rise (Barth and Titus, 1984).

For the contributions of the glaciers, Greenland and Antarctica differential equations have been incorporated, containing input-output factors (in mm/ΔT^* °C).

Uncertainties and Deficiencies of the Model

The simulation model is a reflection of the current state of knowledge. Current knowledge being far from complete, the model has structural limitations.

Scenarios for future trace gas emissions, as presented in this paper, are only indicative, while sources are not fully known or quantified. Positive feedback on microbiological emissions of trace gases by temperature rises is not yet taken into account.

In the climate module trace gas concentrations are converted into global warming effects. Consequently geographical distribution of temperature changes or other climatological features cannot be simulated with the model. Additionally, the scaling of the trace gas radiative effect has been extrapolated beyond the extent of the figures reported. The figures used for converting atmospheric concentrations into temperature rise are based on equilibrium response. It has not yet been investigated to what extent the time lag suppresses the actual temperature in this simulation. No special attention has been paid to the implications of cloud cover and albedo feedback, while water vapour has been taken into account by introducing a water vapour multiplication factor set at 1.7 (Bolle, 1986). At a temperature rise of 2 deg centigrade these mechanisms may be quite different from those at a rise of more than 4 deg. An important spinoff of IMAGE is the possibility of recognizing gaps in our knowledge, which is necessary for a better prediction of the effects of the enhanced greenhouse phenomenon. This may lead to future research priorities. In consequence of the modular structure of IMAGE new information can generally be incorporated without affecting the model structure.

Future Developments

Figure 1 also shows which modules will be added to the existing model in the near future. More trace gases will be studied and built in, such as Ozone, other CFC (especially CFC-113, CFC-114 and CFC-115) and Halons. Secondly a radiative-convective module is being developed including the lag effects between the equilibrium and transient temperature rise, and extended by a pattern of regional differentiation. Additionally, modules of regional changes and impacts on society, such as the effects of sea level rise on the Dutch coastline and water management are recently implemented. The carbon cycle model will be updated and extended by socio-economic factors inducing land use changes, such as deforestation and finally the Edmonds and Reilly Long-Term Global Energy-CO_2 Model will be fully integrated into IMAGE.

Description of Scenarios

Model calculations have been performed with four sets of scenarios, which are based on consistent assumptions for each trace gas. A general survey of these assumptions is given in Table I, while the resulting emissions are depicted in the Figures 2 to 5. In the Figures 6 and 7 example breakdowns of the emissions of CH_4 and N_2O for a particular future year are given. The sets of scenarios are meant to encompass the possible global socio-economical developments in order to illustrate the impact of different future pathways on the greenhouse effect. The highest scenario, A: *unrestricted* trends, assumes a continuation of economic growth, not limited by environmental constraints. Scenario B: *reduced* trends, is meant to include the implementation of environmental measures presently being considered to

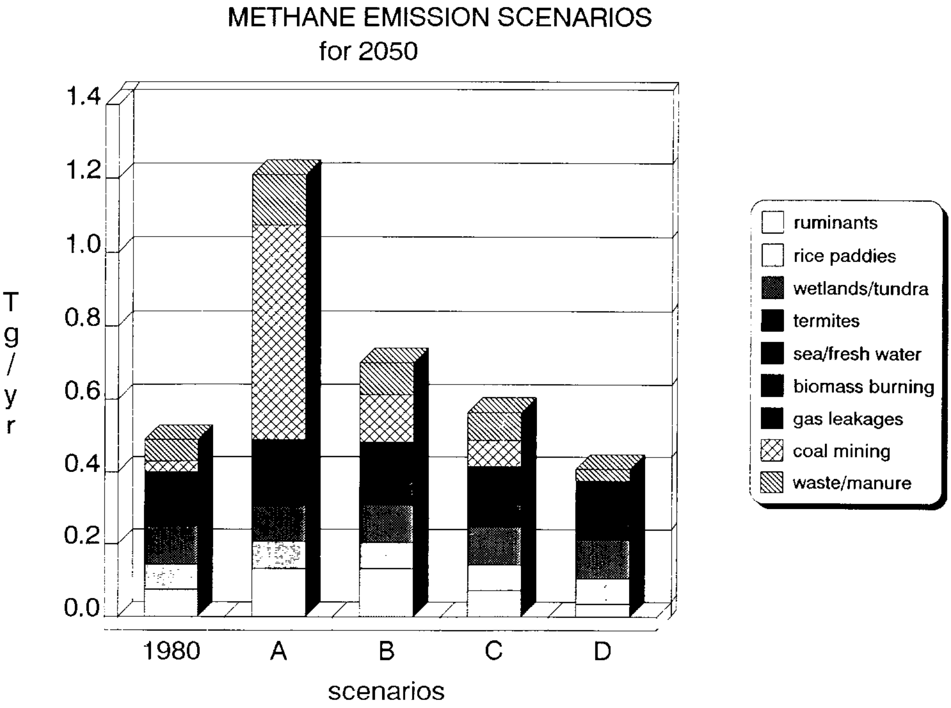

Fig. 6. Build-up of the CH_4-emissions in 2050 (from Swart 1988).

TABLE I: Policy assumptions in scenario sets

Scenario	Trace gas	
	CO_2	CH_4
Continued trends (A)	– major increase energy consumption based on fossil fuels (coal!) – no incentives for increase of energy efficiency – increasing per capita energy use (esp. in third world) – no stimulation renewable and other non-fossil energy – growth not limited by environmental considerations – rapid conversion of available forest resources: shifting cultivation, fuel wood, commercial wood, cattle breeding	– energy scenario see CO_2: major increase in CH_4-emissions from coal mining and natural gas losses – increasing number of cattle (developing countries) – increasing area rice paddies – continuing conversion of tropical forests (emissions from biomass burning, increasing number of termites) – average estimate anthropogenic sources – increasing emissions from waste dumps, especially from growing 3rd world population
Reduced trends (B)	mainly because of price increases (scarcities, some environmental costs): – slight shift towards non-fossil energy sources – minor increase per capita energy consumption – increasing energy efficiency – gradual reduction deforestation rates	– energy scenario see CO_2: important emissions from coal mining – minor increase number of cattle (developing world) – reduction deforestation rates – increasing use of gas from wastes/manure – average estimate anthropogenic sources
Changing trends (C)	environmental concerns lead to modest policy changes: – incentives for increase in energy efficiency – incentives for shift towards renewable energy sources – global efforts to reduce deforestation rates	– energy scenario see CO_2: minor increase energy related CH_4-emissions – after 2000 stabilization number of cattle – increase rice production from intensification, not expansion of wet area – growing recovery of CH_4 from wastes, coal mining – reduction deforestation – low estimate anthropogenic sources
Forced trends (D)	major policy changes because of greenhouse warming concerns: – reduction use fossil fuels – strong efforts towards greater energy efficiency – stagnation world economy – major effort halting deforestation by forest management and reforestation pogrammes	– energy scenario see CO_2: decreasing coal use – major recovery CH_4 from wastes and other sources – halting deforestation – limitation losses from leakages natural gas – after 2000: reduction number of cattle (limitation consumption meat and dairy) – reduction CO-emissions – low estimate anthropogenic sources

TABLE I (continued)

Scenario	Trace gas	
	N_2O	CFCs
Continued trends (A)	– energy scenario see CO_2: enormous increase N_2O-emission from coal use – no emission control measures – rapid increase fertilizer use in third world up to European levels – average estimate anthropogenic sources – continuing deforestation (emission from burning and possible (?) major influence soil emissions)	– continuing trends; continuing growth of economy and cfc-consumption; no full implementation of UNEP-ozone-protocol – no recycling
Reduced trends (B)	– energy scenario see CO_2: large increase N_2O-emissions from coal consumption – gradual increase fertilizer use in third world – gradual reduction deforestation	– implementation basic ozone protocol by ratifiers – production increase by non-ratifiers – minor reduction cfc-losses during production/use – no increase in applications – total result: stabilization of production
Changing trends (C)	– energy scenario see CO_2: increase N_2O-emissions from coal consumption – slight reduction emission rates from fossil fuel combustion – slow increase fertilizer use in third world – major global effort towards halting deforestation	– upgrading ozone protocol: larger production decreases for all countries – reduction of losses and stimulation of recycling – total result: gradual decrease of production
Forced trends (D)	– energy scenario see CO_2: decreasing N_2O-emission due to shift towards non-fossil energy sources and implementation of N_2O-emission control technologies – global program to introduce proper forest management, stop deforestation and start large scale reforestation (influence N_2O-emissions for the future unclear) – limited growth fertilizer use – controlled growth of fertilizer use: type and method of application: limiting N-losses (through denitrification)	– strongly upgraded protocol – stagnancy world economy – elimination of losses – major recycling efforts cfc-refrigerants, foam applications

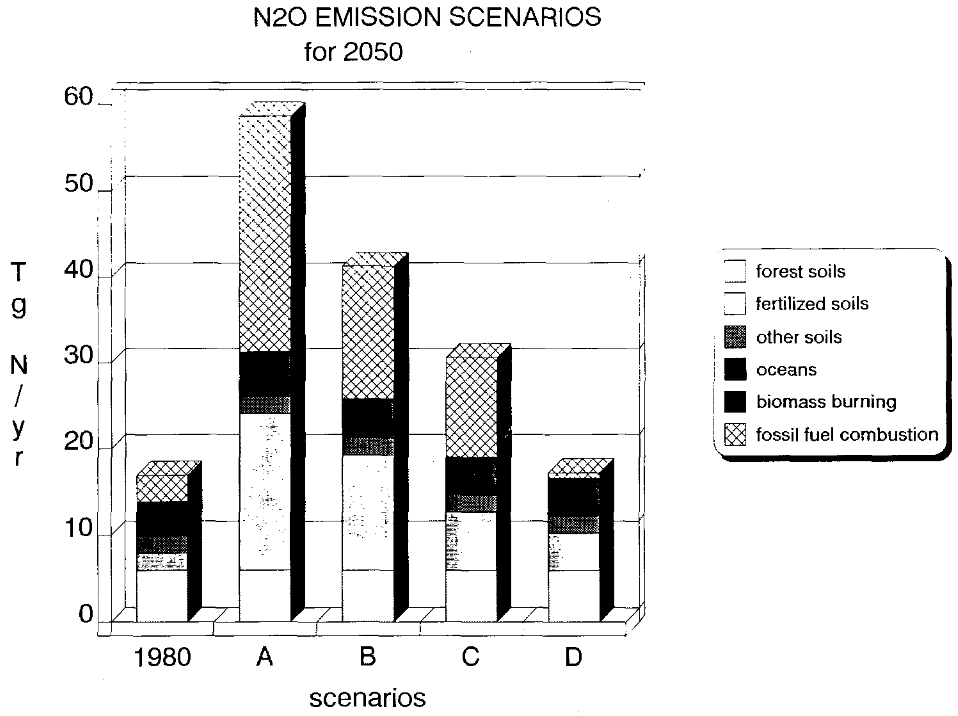

Fig. 7. Build-up of the N_2O-emissions in 2050.

control other environmental problems, like acidification and eutrophication with important side-effects for the greenhouse effect. Scenario C: *changed* trends, assumes the enforcement of a stricter environmental control, at least partly influenced by an international concern about the greenhouse effect as was expressed at some recent conferences (see Jäger, 1988, Environment Canada, 1988). Finally, scenario D: *forced* trends, assesses the possibilities of maximum efforts towards global sustainable development. World population growth, a factor that is assumed not to be influenced by greenhouse policies, is assumed to approach 10.8 billion in 2100 in all scenarios.

Energy Supply

The combustion of fossil fuel is the most important human activity contributing to the emissions of greenhouse gases. The emissions of CO_2 can reasonably well be quantified for different energy scenarios. In the literature distinctions between scenarios are usually very similar to those described above. While the PC-version of the IEA/ORAU Long-Term Global Energy-CO_2 Model (Edmonds and Reilly, 1986, 1987) has not yet been fully integrated into IMAGE, for this paper four Energy-CO_2 scenarios have been reproduced with this model separately, using the input data given by Mintzer (1987). His scenario assumptions coincide very well with the four types of world development described above. Like population growth, labor productivity growth, the main driving factor for economic growth, is assumed to be common for all scenarios and, while varying among the different regions, averages 1.8% annually. The energy related emissions of CH_4 and N_2O are less well-defined than those of CO_2 but may play an important role in the greenhouse problem. For the purpose of the IMAGE-calculations average estimates for the emissions of the different sources of these gases are assumed to be valid for 1980 and future emissions are determined by assessing developments of these sources along the lines described above. Unabated CH_4 emissions from the mining of coal and the exploitation of natural gas are assumed to be proportional to the consumption of these fuels, while unabated N_2O emissions from fossil fuels are taken proportional to the consumption of coal and oil. Especially because of the expected long term increase in the use of coal, better information is needed about the methane emission rates from coal mining (both open pit and deep mining) and the nitrous oxide emission rates from coal combustion. The most important policy tools are efficiency improvements for supply, conversion and end use, cost assumptions for renewables and synfuels, environmental costs (or taxes) for supply and end use and abatement of energy related emissions of methane and nitrous oxide.

In the high (A: *unrestricted trends*) scenario economic growth is based on an increase in fossil fuel consumption, especially coal because of the higher prices of the decreasing oil and gas resources. It should be noted, that in the results from the Edmonds and Reilly model recent discoveries of major natural gas reserves are not yet included. They will be included when coupling the model to IMAGE. In this scenario environmental concerns neither alter ways of life nor lead to substantial efforts to reduce emissions. Introduction of renewable energy is retarded (e.g. solar energy at US$ 20.–/GJ) and production of synfuels enabled by relatively low prices (e.g. non-energy prices for synoil at $ 3.50/GJ, for syngas at $ 2.75/GJ). End use efficiency increases by only 0.2% annually and the efficiency of coal supply increases more (0.75% yr^{-1}) than the efficiency of fuels with lower CO_2-emission factors (e.g. gas 0.3% yr^{-1}). No major environmental costs are assumed. Coal having the highest CO_2-emission rates this scenario leads to high CO_2-emissions. The effects of these high emissions may even cause a negative feedback in the next century, climatological change affecting economic growth and food production. This is not taken into account yet. High temperature combustion of coal and other fossil fuels causes increasing N_2O-emissions (Hao *et al.*, 1987; Kavanaugh *et al.*, 1987).

The unabated release of methane during the exploitation of coal reserves may cause a sharp increase in CH_4-emissions. However, further research into this aspect for different methods of coal mining is needed to confirm this statement. The results are particularly interesting, since recent research suggests, that the contribution of fossil sources to methane increase may have been underestimated (Lowe *et al.*, 1988).

Because of a rather stable supply of natural gas in all scenarios in absolute terms, CH_4-emissions from leakages will not alter much. It may be assumed, that efforts to reduce leakages will compensate for emissions caused by possibly increasing transport distances.

In the *reduced trends* scenario (B) the introduction of non-fossil fuels is accelerated and energy efficiency increased because of higher price of fossil fuels, influenced by scarcity and environmental measures. The costs of solar energy are assumed to be lower than in scenario A (US$ 16.50/GJ) and end-use efficiency increases by 0.8% annually. Supply efficiency for gas and oil are assumed to increase faster (0.3% annually) than for coal (0.2%). Synfuels are relatively more expensive ($ 4.25 non-energy costs for synoil and $ 3.15 for syngas). Moderate environmental costs for coal supply are introduced. Methane is a useful gas and therefore the reduction of losses is not only interesting from the environmental point of view. A gradual increase of the methane recovery from coal mining up to 25% in 2100 is assumed. This might be a scenario including the implementation of the environmental strategies presently being considered. CO_2- and CH_4-emissions from coal combustion and mining are still high.

In the *changed trends* scenario (C) environmental strategies will be upgraded. Incentives accelerate the introduction of renewable energy sources (e.g. solar US$ 15.00/GJ). End-use energy efficiency increases by 1.0% annually and supply efficiency increases more for gas (0.4% yr^{-1}) than for oil (0.3%) and coal (0.2%). Higher prices delay the introduction of synfuels (synoil $ 5.– and syngas $ 4.– non-energy prices). Again 25% of the methane from coal mining is assumed to be recovered in 2100. Higher environmental costs are introduced for coal. Increased energy consumption, especially in the Third World will still cause a considerable increase of coal consumption.

The only scenario showing a continuation of, or in the long run, a return to present day emission rates is the *forced trends* scenario (D). Concern about the global environment will lead to a change in lifestyle in the developed world, combined with the introduction of very energy efficient technologies using renewable energy sources both in developed and developing countries. This will lead to low per capita energy consumption of fossil fuels rather than the introduction of expensive emission control technologies enabling a sustainable development of global societies (Mintzer, 1987; Goldemberg *et al.*, 1987; Cheng *et al.*, 1986). Costs of solar energy are assumed to arrive at US$ 12.–/GJ in 25 yr. End-use efficiency increases by 1.5% annually and supply efficiency for natural gas (1.5% yr^{-1}) increases much faster than for oil (0.6%) and coal (0.2%). High prices (synoil $ 7.– and syngas $ 5.50 non-energy costs) and low energy consumption prevent the introduction of synfuels. Environmental costs (taxes) proportional to their carbon content are applied to supply of the different fuel types and their consumption. Remaining N_2O-emissions are assumed to be reduced by technological measures. 50% of the CH_4-emissions from coal mining are finally recovered.

Agriculture

Although energy production and consumption is the main contributor to the greenhouse effect, agricultural activities also influence the emission of trace gases: methane from cattle and rice paddies, nitrous oxide from fertilization and probably carbon dioxide from deforestation. Again the preliminary scenarios for methane and nitrous oxide (both anthropogenic and natural) are based on average base year estimates from a variety of sources, Sheppard *et al.* (1982), Khalil and Rasmussen (1983, 1985), Atmospheric Ozone (1985), Van Ham (1987), WMO (1986), Bolle *et al.* (1986), Holzapfel-Pschorn and Seiler (1986), Bingemer and Crutzen (1987), Crutzen *et al.* (1986), Seiler (1984) for methane and Keller *et al.* (1986), Van Ham (1987), Conrad *et al.* (1979, 1983), Marland and Rotty (1985) for nitrous oxide. Scenario assumptions are rough estimates; compared to the figures of the Food and Agricultural Organization (1987) they tend to be low.

In the *unrestricted trends* scenario it is assumed, that food production will keep up with population growth through massive intensification of agricultural production by way of fuel or mined mineral based technologies, including fertilizers and irrigation. The sustainability of such a scenario may be questioned.

Because of an increase of agricultural land and intensity of fertilizer application the use of nitrogenous fertilizers will increase the still uncertain N_2O-emissions by more than 4 times by the year 2100. For the increase in arable land logistic curves are used, fitted to historical FAO-data and consistent with estimates of potential arable land. Although the area available for rice cultivation will probably not be extended very much, the remaining arable area becoming scarce and erosion causing loss of fertile soil, irrigation of the present rainfed area is assumed to lead to increases of CH_4-emissions by almost 80% in 2100. Again logistic curves are applied utilizing FAO-data for historical development of rice paddy area. With an increasing number of countries reaching higher levels of prosperity, an increasing consumption of meat and dairy products will lead almost to a doubling of the number of methane producing cattle, mainly in the now developing world. This doubling still implies a reduction of per capita consumption because of the growing world population.

The unrestricted economic growth in this scenario will further exploit the tropical forests. Cattle breeding, cultivation of export products, production of logs and fuelwood, mining or infrastructural projects, all force the increasing rural population further into the remaining forests, practising a form of slash and burn agriculture, which is often not sustainable due to shorter rotation times and unsuitable soils (Wold Resources Institute, 1986, 1987; Molofsky *et al.*, 1986). This affects the emissions of several trace gases: more CO_2 will be released into the atmosphere. The effects as to CH_4, and N_2O are still unclear. Tropical soils serve as a sink for CH_4, higher rates being observed for savannahs than for forest soils. N_2O-emissions from tropical forest soils are important and may increase after forest conversion. As the number of termites increases when tropical forests are being converted, emissions by termites may increase.

In the *reduced trends* scenario (B) the high costs of agricultural inputs to increase productivity and irrigated areas decrease the present growth rates of fertilizer use and irrigation, thus limiting the agricultural emissions of CH_4 and N_2O. The number of cattle gradually increases by 75% in 2100, fertilizer use increases by 250% and rice paddies by about 40%. Deforestation rates are gradually slowing down.

In the *changed trends* scenario (C) the changes of scenario B are accelerated: increases in productivity are sought in intensification based on agro-ecological practices rather than technological means, although use of fertilizer remains essential in order to meet food demands, causing a 150% increase in fertilizer consumption globally in 2100. A global effort to control deforestation is initiated. The number of cattle increases by only 50% compared to a doubling of the human population. CH_4-emissions from rice paddies increase finally by only 25%. Agricultural wastes are increasingly used for energy production.

The *forced trends* scenario (D) reflects a worldwide change of attitude towards agricultural practises. The use of fertilizers and pesticides is limited to the necessary minimum, agricultural development fully aiming at sustainability at the local or regional level. This scenario is dependent on the spread of sustainable agro-ecological techniques, to be fully developed yet (e.g., see Dover and Talbot, 1987). Still a global increase in nitrogen fertilizer (80% in 2100) is assumed to be unavoidable. To optimize food efficiency per capita meat consumption is limited, leading only to a small increase (10% in 2100) of the number of cattle and the associated methane emissions.

All agricultural wastes (crop residues, manure) are used for fertilizers or energy production. An effective global programme stops deforestation and stimulates proper forest management and reforestation. All these activities limit emissions of CO_2, CH_4 and N_2O, and even change the direction of present trends.

CFC-Use

In the *unrestricted trends* scenario it is assumed that the ozone protocol is not fully implemented: production and use will be increasing, albeit at a moderate rate, and will stabilize in the first half of the 21st century.

In the *reduced trends* scenario the Montreal protocol (United Nations Environment Programme, 1987) is supposed to be implemented by linearly decreasing the production towards the limits set for 1993 (80%) and 1998 (50%), making use of the allowance (10% and 15% respectively) to 'satisfy basic domestic needs' and 'for the purpose of industrial rationalization' followed by stabilization after 1999. The allowed growth of production planned is not taken into account because of lack of data, while no substances other than CFC-11 and CFC-12 are yet being considered in IMAGE. The objectives are reached by turning to substitues, limiting losses and increasing recycling gradually.

In the *changed trends* scenario the basic protocol is upgraded to a limit of 15% of the 1986 production and consumption figures for 1998, after which year production and consumption are assumed to stabilize.

No additional production capacity is built, since this seems to be useless under these circumstances. The efforts towards the development of 'safe' substances, recycling and loss reduction are increased.

In the *forced trends* scenario a total ban is assumed in 2050 in addition to the 85% reduction in scenario C. A possibly remaining use for purposes considered essential is neglected.

Other Trends

Methane emissions from waste dumps are increasing with population and the level of prosperity. In the scenarios from A to D an increasing percentage of methane recovery from waste is assumed (in 2100 0%, 20%, 30% and 50% respectively).

Other possibly influencing factors are kept constant because of lack of even qualitative information. Forest and bush fires may increase with population, and the increasing CO_2-concentrations will probably increase the release of CH_4-emissions from anaerobic microbiological sources. The reclamation of wetlands may reduce CH_4-emissions, but temperature rises may melt the permafrost in the arctic regions, increasing the 'wetland' areas.

Results

Concerning the greenhouse problem the items referred to most are the time when doubling of the initial atmospheric CO_2-concentration will occur (Figure 8) and the consequent temperature increase (Figure 13).

Figure 8 shows that the doubling will be reached in about 2060 (scenario A), 2075 (scenario B), 2100 (scenario C) or even after 2100 (scenario D). Verification of the simulated trace gas concentrations while starting simulations in 1900, resulted in an approximation of the CO_2-concentration from 1959–1985 with an accuracy of more than 99%.

The airborne fraction, as defined in (1), is represented in Figure 9. Worth mentioning is the fact that a continuous decrease takes place in the airborne fraction, as a consequence of the C-cycle interpretation by Goudriaan and Ketner (1984). From the results of the calculations with the carbon cycle module the biosphere appears to have been an important carbon source in the past, but a minor sink at present. Although still resulting in a positive carbon flux from the biosphere, estimates of other authors also show a declining trend (Houghton *et al.* 1983, 1985, 1987; Detwiler and Hall, 1985, 1988).

The effects of deforestation, although a major human alteration of the biosphere

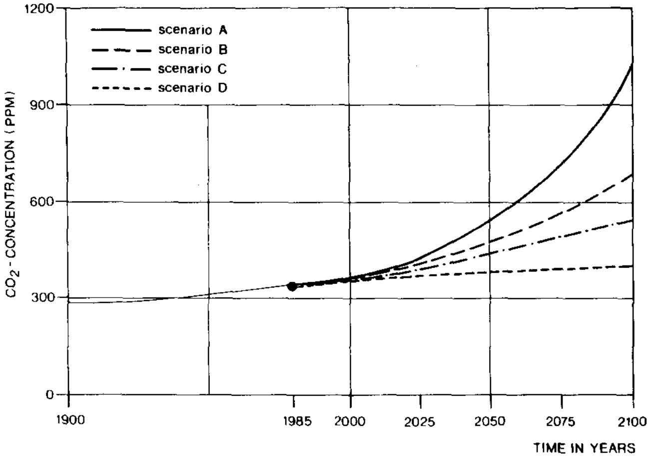

Fig. 8. Concentration of CO_2.

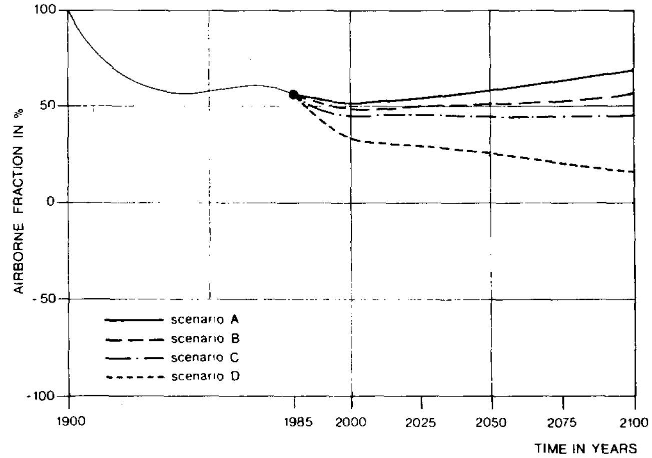

Fig. 9. Airborne fraction.

and mentioned in the scenario assumptions, would be limited, according to the present version of the module, while the releases of carbon dioxide by burning are probably outweighed by the effects of CO_2-induced growth and a relatively high rate of conversion of biomass to charcoal. Presently the module and its data are updated and refined to check these results.

Figure 10 shows the CH_4-concentrations. Scenario A and B result in an upward trend with a deflecting curve after 2050, scenario C shows a relatively constant methane concentration and scenario D leads to a slightly decreasing concentration. It should be noted, that no temperature feedback on methane-emissions has been taken into account. In our model in the second half of the 21st century the growth of the CH_4-concentrations reverses due to accounting increase of OH-concentration. This increase is caused by a combination of stabilizing CO-emissions and continuing OH-production.

The N_2O-concentration is given in Figure 11. Due to the long atmospheric lifetime of this gas all emission scenarios lead to an increase of the concentrations.

Figure 12 gives the CFC-12 concentration. Although the influence is undeniable, the UNEP ozone protocol cannot prevent CFC-11 and CFC-12 concentrations from increasing over the next decades.

Only by upgrading the Montreal Protocol (scenario C) can the concentrations of CFC-11 and CFC-12 be maintained on the present level. Other ozone depleting substances, of which some are also not yet included in the Montreal protocol, have not yet been taken into account. Therefore our results can even be considered optimistic. Due to the long atmospheric lifetime of CFC even further reduction of

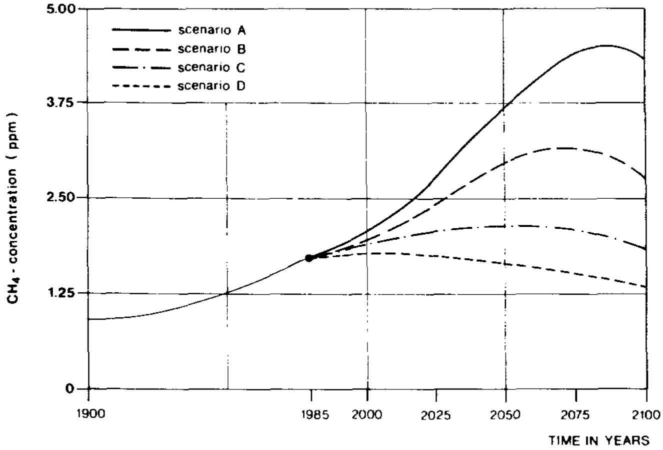

Fig. 10. Concentration of CH_4.

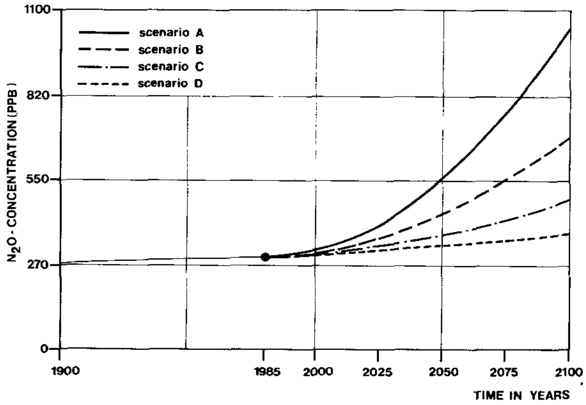

Fig. 11. Concentration of N_2O.

emissions (scenario D) is needed to lower CFC-concentrations in the second half of the next century.

The results of combined calculations as shown in Figure 13 are quite surprising. Even at the most restrictive scenarios of emissions a 1.5 °C increase of the equilibrium temperature will occur before 2020. Actually for 1980 a global equilibrium temperature increase of 0.95 °C has been simulated. This is high, due to the parameterized water vapour contribution, but in line with other models (Dickinson, 1986; Wigley, 1987). Double the amount of CO_2 in scenario set A results in an increase of 2.3 °C, while the total effect then of all trace gases is a 4.75 °C increase.

Figure 14 gives the relative contribution of the individual trace gases to temperature rise, which varies over the scenario sets and is time dependent. The contribution of methane to the total temperature effect is remarkable. A present 37% con-

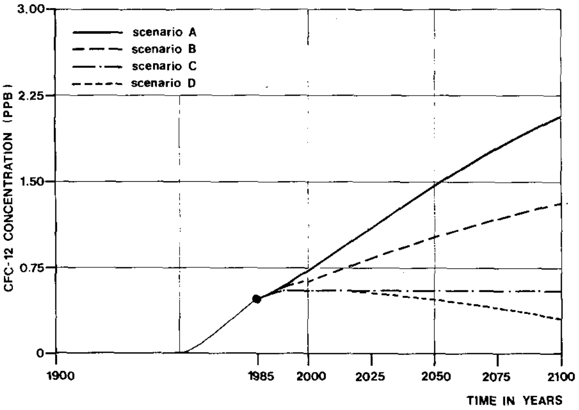

Fig. 12. Concentration of CFC-12.

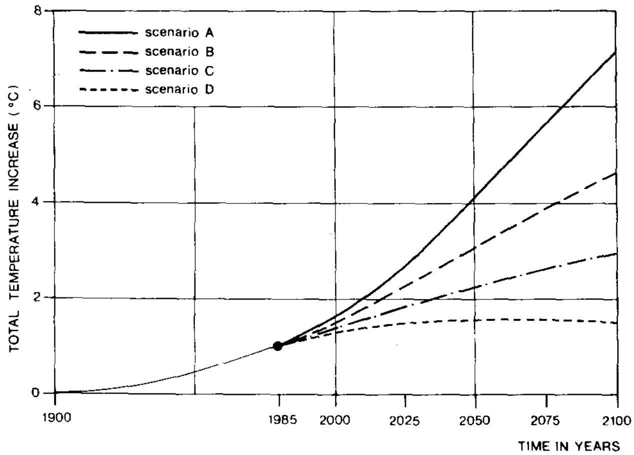

Fig. 13. Total temperature increase.

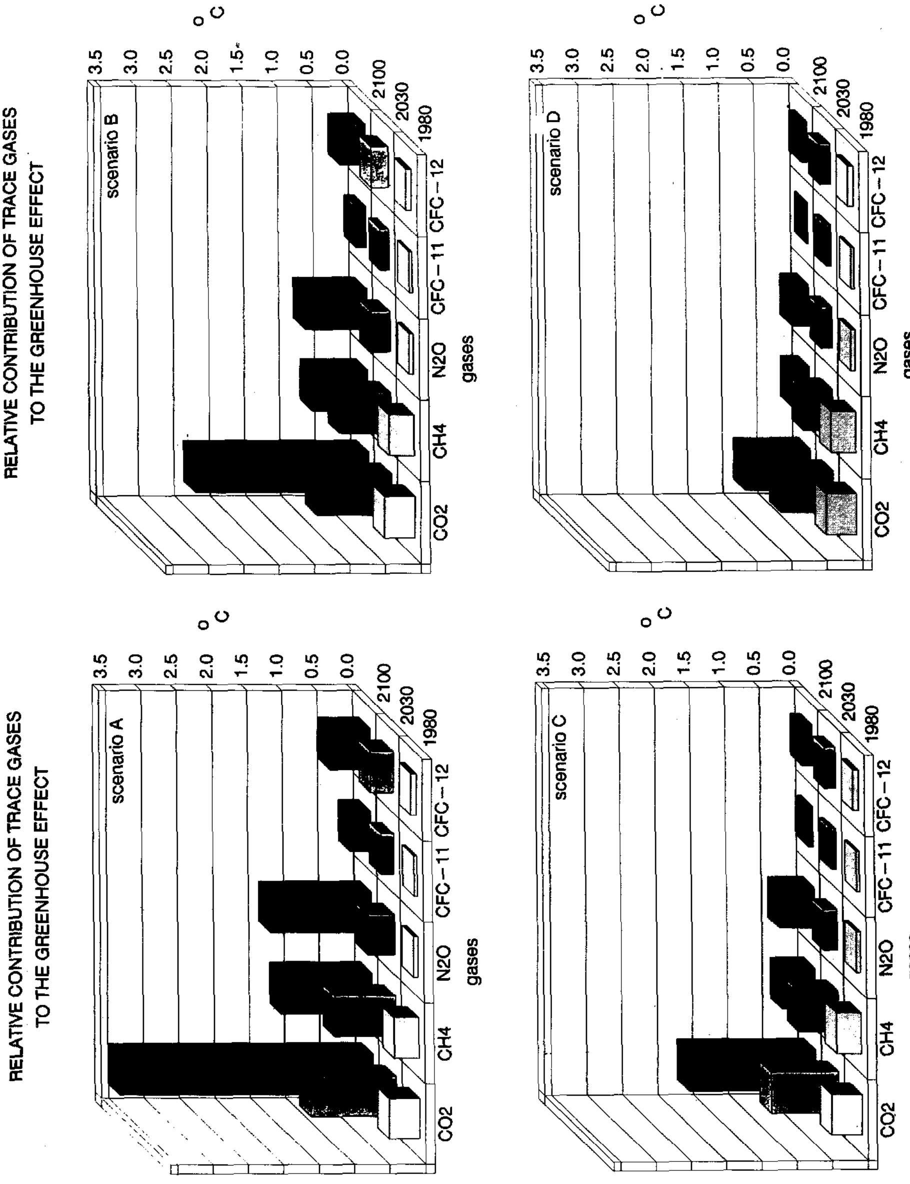

Fig. 14. Relative contribution of trace gases to the greenhouse effect.

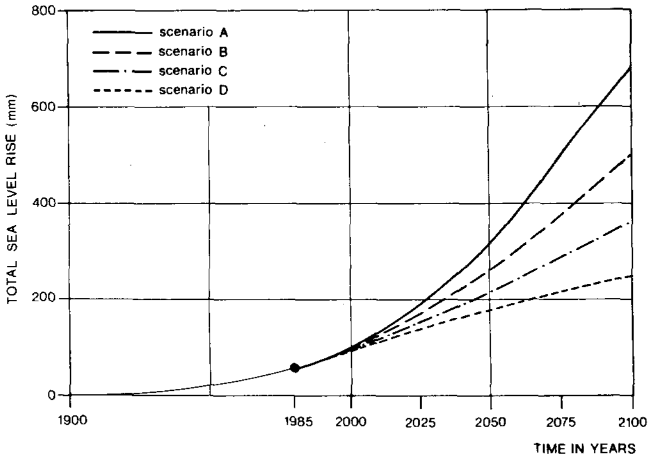

Fig. 15. Total sea level rise.

tribution is found to decrease to 16 to 18%. Next to the relatively short lifetime, this might be caused by the probability that methane emissions are mostly related to population numbers, while the emissions of the other gase are more related to their consumption levels.

Because of this aspect and its long lifetime, nitrous oxide appears to become increasingly important. Recent evidence of systematic errors in the sample analysis has not been taken into account yet.

In Figure 15 the sea level rise is given. The estimates vary from approximately 25 cm to 70 cm in 2100. In these results the present trend of 10–15 cm century^{-1} is ignored. In the module Antarctica will contribute to a lowering of the sea level, while Greenland will cause a sea level rise. The total net model effect of Greenland and Antarctica is a lowering of the sea level, varying from 5 to 10 cm.

Comparison with Other Models

Recently in Washington IMAGE was compared to the Model of Warming Commitment of the World Resources Institute (Mintzer, 1987), which is the only comparable integrated greenhouse policy model published to date. Generally, the structures of both models are similar. Some of the major differences will be discussed in this section.

In IMAGE simulation starts in 1900, while 1985 is the starting year of the WRI model. The present energy end-use and cfc modules of WRI are more detailed than in IMAGE. IMAGE includes a carbon cycle, reflected by an ocean module coupled with a terrestrial biota module; the WRI model uses exogenous variables instead of a carbon cycle model. The CO_2-emission by deforestation in IMAGE is not an exogenous variable like in the WRI model, but is integrated in the biosphere component of the carbon cycle module. For methane, IMAGE includes a CH_4-CO-OH cycle incorporating emissions of methane and carbon monoxide, while the WRI model only takes CH_4 concentrations into account. Most obvious additional features of IMAGE are the effect modules, of which the sea level module is discussed here. IMAGE-runs were performed with the same input emission scenarios as used in the WRI model. It appeared that the resulting equivalent CO_2 concentrations and temperature changes were not significantly different. Among other things this exercise confirmed the reproducibility of the results. One important reason for the differences appeared to be the different treatment of the biospheric component of the carbon cycle.

Conclusions

- IMAGE demonstrations for policy makers have shown that an integrated cause-effect model of the greenhouse effect for science-based policy purposes is useful. It is possible to derive sets of allowable emissions from a target set for climate impacts. It also enables scientists working in the field of climate change to put their efforts in a wider perspective. The model can be easily adapted to changed or increased knowledge.
- Continuation of the recent trend of emissions of the relevant trace gases leads to a rapid rise of the mean global temperature.
  Temperature rise can be delayed considerably by the timely adoption of sometimes radical measures. Most effective are policies towards energy conservation and non-fossil fuels, which are presently unattractive given the low energy prices. Increase of efficiency with low inputs in the agricultural sector also contributes, albeit moderately, to the delay of the greenhouse effect.
- The most conservative scenario used in the simulations (D: *forced trends*) leads to an accelerating sea level rise (25–30 cm) which is far beyond the trend of the last 100 yr (10–15 cm in the last century). Nevertheless, many uncertainties exist about the rate of the sea level rise. However, in the future the sea level rise will probably pose a major threat to coastal lowlands, while the time needed for infrastructural adjustments requires ample advance planning.
- So far calculations with the carbon cycle module (Goudriaan and Ketner 1984) show, that the contribution of deforestation to the greenhouse effect presently is minimal and in most scenarios even negative. This is caused by the inclusion of CO_2-enhanced growth and relatively high estimates of the conversion of biomass into charcoal during burning.
- Methane presently is an important greenhouse gas. The relative role of methane is expected to decrease because methane has a relatively short lifetime, the potential development of sources tends to be slower than that of other gases and emission reduction and recovery measures are possible.
- In the long run N_2O will become a greenhouse gas of great importance. Even the most optimistic N_2O-emission scenario leads to a rise in temperature. Policy measures can probably affect the N_2O-concentrations. Additional research is

needed to improve the knowledge on the sources and the validity of measurement techniques.

- The effect of the implementation of the Montreal Protocol is important to stabilize the relative role of CFC in the greenhouse effect. To decrease this role, it seems to be necessary to improve the agreement extensively.

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