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The Effectiveness of Measures to Reduce the Man-Made Greenhouse Effect. The Application of a Climate-Policy Model

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With 7 Figures

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Summary

In this paper we briefly describe the characteristics and the performance of our 1-D Muenster Climate Model. The model system consists of coupled models including gas cycle models, an energy balance model and a sea level rise model. The chemical feedback mechanisms among greenhouse gases are not included. This model, which is a scientifically-based parameterized simulation model, is used here primarily to help assess the effectiveness of various plausible policy options in mitigating the additional man-made greenhouse warming and the resulting sea level rise.

For setting priorities it is important to assess the effectiveness of the various measures by which the greenhouse effect can be reduced. To this end we take a Scenario Business-as-Usual as a reference case (Leggett et al., 1992) and study the mitigating effects of the following four packages of measures: The Copenhagen Agreements on CFC, HCFC, and halon reduction (GECR, 1992), the Tropical Forest Preservation Plan of the Climate Enquete-Commission of the German Parliament on CO_2 reduction (ECGP, 1990), a detailed reduction scheme for energy-related CO_2 (ECGP, 1990), and a preliminary scheme for CH_4, CO, and N_2O reduction (Bach and Jain, 1992–1993).

The required reduction depends, among others, on the desired climate and ecosystem protection. This is defined by the Enquete-Commission and others as a mean global rate of surface temperature change of ca. 0.1 °C per decade – assumed to be critical to many ecosystems – and a mean global warming ceiling of ca. 2 °C in 2100 relative to 1860.

Our results show that the Copenhagen Agreements, the Tropical Forest Preservation Plan, the energy-related CO_2 reduction scheme, and the CH_4 and N_2O reduction schemes could mitigate the anthropogenic greenhouse warming by ca. 12%, 6%, 35%, and 9% respectively. Taken together, all four packages of measures could reduce the man-made greenhouse effect by more than 60% until 2100; i.e. over the climate sensitivity range 2.5 °C (1.5 to 4.5) for $2 \times CO_2$, the warming could be reduced from 3.5 °C (2.4 to 5.0) without specific measures to 1.3 °C (0.9 to 2.0) with the above packages of measures; and likewise, the mean global sea level rise could be reduced from 65 cm (46 to 88) without specific measures to 32 cm (22 to 47) with the above measures.

Finally, the model results also emphasize the importance of trace gases other than CO_2 in mitigating additional man-made greenhouse warming. According to our preliminary estimates, CH_4 could in the short term make a sizable contribution to the reduction of the greenhouse effect (because of its relatively short lifetime of 10 yr), as could N_2O in the medium and long term (with a relatively long lifetime of 150 yr).

1. Introduction

Global warming poses one of the greatest threats to society. Therefore, the climate system and the ecosystem have to be protected. The major underlying causes of climatic change are the wasteful use of fossil fuels, as well as the destruction of the tropical and extra-tropical forests and soils. The danger is real that the climate and the environment, common goods for all of mankind, will be altered irreversibly if control measures are not taken now. By the time the symptoms of such action become visible to everybody, it is in all likelihood too late for countervailing measures. Society cannot afford to wait for the confirming diagnosis which only a post-mortem of patient Earth can supply. Responsibility to present and future generations demands from us to proceed on the principle of precaution and to begin, already now, with the introduction of the necessary measures.

What emission reduction is necessary depends, among others, on the required level of climate and ecosystem protection. Some guidance is given by the Enquete-Commission of the German Parliament (ECGP, 1989), which has defined the described climate and ecosystem protection as the mean global rate of surface temperature change of 0.1 °C per decade between 1990 and 2100, and as a mean global warming ceiling of 2 °C by 2100 as compared to 1860. Conference statements, such as that of the Villach Climate Conference, and society statements, such as the joint statement of the German Physical and Meteorological Societies, go in the same direction. Very significantly, the Framework Convention on Climate Change, which was signed by the required 50 nations at the UNCED in Rio in 1992, states as its ultimate objective (INC, 1992)... "the stabilization of greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". This aim perfectly agrees with that given by the Enquete-Commission, and that pursued in this paper.

Now, what is climatically required and what seems technically and economically feasible must be made to match. Priority should be given to those measures which can best help break away from the self-destructive growth dynamics and bring about a restructuring of the traditional economic and social structures. To this end we have developed a climate-policy oriented model – the 1-D Muenster Climate Model – which is a scientifically-based parameterized simulation model. The primary objective of this model is to help assess the effectiveness of various plausible policy options in mitigating the additional anthropogenic greenhouse effect. This model was extensively used for the decision-making work of the Enquete-Commission (for example in ECGP, 1991).

Here we present the results of our investigations showing to what extent four packages of measures can help mitigate the man-made greenhouse warming and the resulting sea level rise. Specifically, we start from a Scenario Business-as-Usual (BAU), i.e. the continuation of current emission trends, as a reference case (Houghton et al., 1992), and then show successively the effects of the following four packages of measures: The Copenhagen Agreements on CFC, HCFC, and halon reduction (GECR, 1992; Gehring and Oberthur, 1993), the Tropical Forest Preservation Plan of the Enquete-Commission on CO_2 reduction (ECGP, 1990), a detailed reduction scheme for energy-related CO_2, and a preliminary reduction scheme for CH_4 and N_2O. First we give a brief description of the model and its performance.

2. Model Description

Figure 1 shows the coupled model concept employed, basically consisting of several models converting emissions of major greenhouse gases to concentrations, an energy balance climate model for the atmosphere and the ocean, and a sea level rise model. These are linked in a simple way: the output of one model serves as input for the next one. The following greenhouse gases contributing to the additional man-made greenhouse effect are used as input: CO_2, CH_4, N_2O, CFC-11, -12, -113, -114, -115, HCFC-22, halon-1301, carbon tetrachloride (CCl_4), methylchloroform (CH_3CCl_3), tropospheric ozone, and stratospheric water vapor. We do not take into account the effects of other HCFCs, such as HCFC-134a, because of the large uncertainties in estimating both past and future emissions. The greenhouse effect is modelled as a dynamic process with discrete time steps of one year and a simulation period of 240 years, i.e. from 1860 (the beginning of the industrial era) to 2100. The model runs to simulate the periods of 1860 to 1990 and 1990 to 2100 are based on estimates of historical emission data and on specific scenarios. Here we give only a brief overview. A detailed description of the various coupled models is given by Bach and Jain (1992, 1992–1993), Piehler et al. (1991) and Jain and Bach (1992).

2.1 Concentration Models

The concentration of CO_2 is calculated by a box-diffusion carbon cycle model which consists of 3 reservoirs, namely the atmosphere, the mixed ocean layer (ca. 75 m deep), and the deep ocean (ca. 4000 m deep). The model equations which describe the rate of change of carbon in each

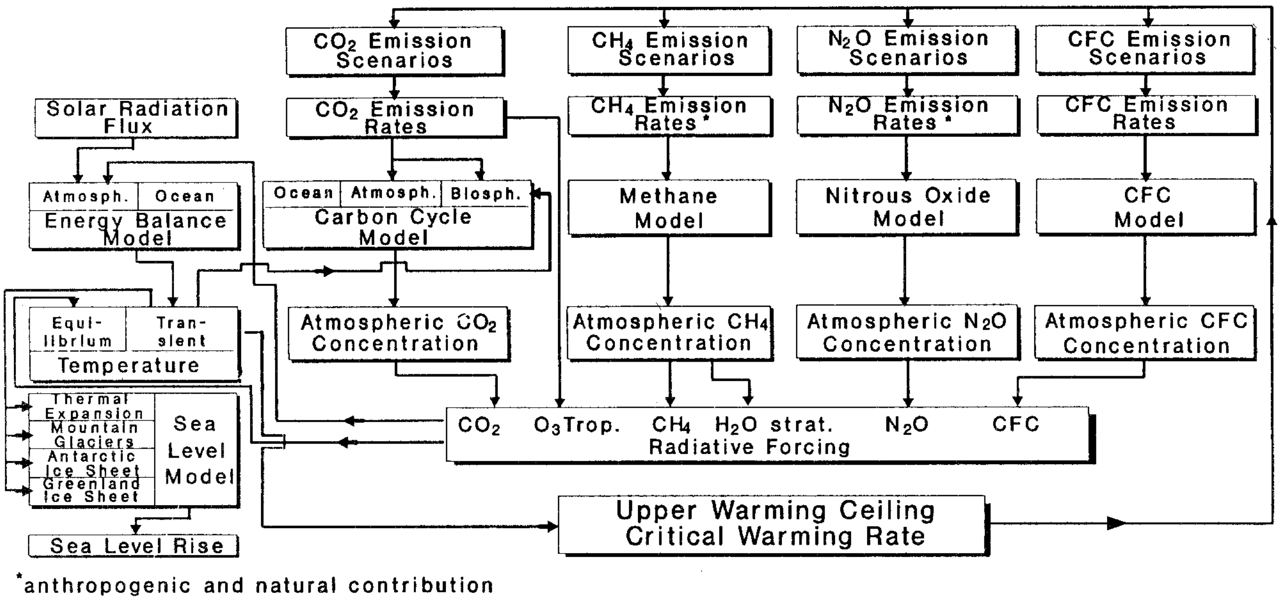


Fig. 1. Concept of the Muenster Climate Model (see text for O_3)

box are those taken from Oeschger et al. (1975). The model ocean is treated as a diffusion medium with constant vertical eddy diffusivity ($K = 4000\,m^2\,yr^{-1}$). The buffer effect of the sea water is taken into account by multiplying the CO_2 flux from the mixed layer to the atmosphere by a buffer factor which is estimated from the full set of chemical equations describing the various chemical equilibria of the reaction system as given by Hoffert et al. (1979). The model also takes into account the interaction with the biosphere. For better performance we replaced the simple biosphere scheme in the Oeschger model by the multi-box globally averaged terrestrial biosphere model (version 8) developed by Harvey (1989a). The photosynthesis rate is simulated by increasing CO_2 concentration in the atmosphere by a logarithmic law and a fertilization factor $\beta = 0.4$. The flow coefficients are temperature-dependent according to Arrhenius' Law.

The past and future atmospheric CFC, halon and N_2O concentrations are calculated by a simple mass balance model described by Bach and Jain (1990). The removal rates of CFCs and N_2O are assumed to be inversely proportional to the atmospheric lifetimes. In these models, the annual concentrations of a specific gas are determined by their initial concentrations, emissions and removal rates.

The CFC content in the atmosphere is calculated not directly from the amount produced but from the amount that has actually escaped into the atmosphere. Products of CFC-11 and CFC-12 can be divided into four categories, namely, prompt emitters (aerosol and open cell foam), hermetically-sealed refrigeration, non-hermetically-sealed refrigeration and closed cell foam. Emission characteristics of these product classifications have been assessed using the assumptions of Gamlen et al. (1986). Most of the CFC-113 is emitted promptly, but an estimated 15% of the production is lost in waste disposal, dumps, and incinerators (Hammitt et al., 1987). Thus, for calculation purposes, we assume that world emission of CFC-113 is 85% of world production. Halons are largely banked in the fire extinguishing systems. Small amounts are emitted through leakage, fire practices, and when the units are disposed. Thus, it is assumed for halons that the total annual production is added to the quantity that is already stored in the bank, and that a fixed fraction of this bank is emitted annually according to the procedure described by Bach and Jain (1990). CFC-114, -115, CCl_4, HCFC-22, and methyl chloroform are being released shortly after their production, so that their annual emission is assumed to be equal to their production.

The methane burden of the atmosphere is calculated by simulating the main atmospheric chemical processes influencing the global concentrations of CH_4, CO, and OH, using the global

CH_4-CO-OH cycle model developed by Rotmans et al. (1990). The removal rates of CH_4 and CO are determined from the uptake by soils, transport to the stratosphere, and oxidation by OH radicals. We assume the uptake velocity by soils and the transport velocity to the stratosphere to be time-independent, although there is evidence that these values change with time (Watson et al., 1990). The concentration of OH radicals is determined by the photochemical balance between production of OH and the loss rate due to reaction with CH_4 and CO (Levine et al., 1985). The reaction rate constants for the reactions of CH_4 and CO with OH are taken from the measurements by Vaghjiani and Ravishankara (1991). Using their data the model-estimated atmospheric CH_4 life-time in 1990 resulted in 10.7 years which is in agreement with the value quoted in Watson et al. (1992). Ozone is the source of hydroxyl in the troposphere, and the nitrogen oxides (NOx) are the photochemical source of tropospheric ozone. Under low-NOx conditions, methane oxidation reactions result in a decrease of O_3 and OH. When high-NOx conditions exist, methane oxidation results in a net increase of O_3 and OH. In this study we assume a low-NOx case. This should be more representative of the global atmosphere since NOx concentrations are, at 5–20 pptv, very low over the oceans which cover most of the earth's surface (Wuebbles and Tamaresis, 1991).

2.2 Climate Model

We use the globally averaged energy balance climate model developed by Harvey and Schneider (1985). This box-advection diffusion model contains a vertically integrated atmosphere box, an equivalent mixed ocean layer box (75 m), an advective-diffusive deep ocean (ca. 4000 m), and a thin slab representing land thermal inertia. In the deep ocean heat is transported upwards with an advection velocity of 4 m yr^{-1}, and downwards by physical processes represented by a single, effective diffusion coefficient of 0.6 $cm^2 s^{-1}$. Perturbations in the net radiative forcing from CO_2 and other trace gases are computed using formulae of Wigley (1987), Bach and Jain (1990), as well as Shine et al. (1990), which were derived from detailed radiative transfer models. For stratospheric H_2O the radiative forcing is approximately 30% that of CH_4 (Shine et al., 1990). The contribution of stratospheric H_2O is very uncertain. Recent studies have shown that Shine et al. (1990) overestimated the indirect effects of stratospheric H_2O (Lelieveld and Crutzen, 1992; Rind and Lacis, 1993; Hauglustaine et al., 1994). However, its contribution is very small, amounting to a maximum of 0.4 Wm^{-2} by 2100. Since the increase of tropospheric O_3 is related to fossil fuel use (Ramanathan et al., 1987), it is assumed that tropospheric O_3 forcing decreases in proportion to fossil fuel CO_2 emissions once these emissions begin to decrease (Harvey, 1989b). The contribution of NOx to the greenhouse effect as a precursor of the greenhouse gas ozone is not considered in this study.

The response of the climate system to the changes in radiative forcing is principally determined by the climate sensitivity here defined as the equilibrium surface temperature increase for carbon dioxide doubling, ΔT_{2x}. This parameter accounts for all the climate feedback processes. General circulation model estimates for ΔT_{2x} range from 1.5 to 4.5 °C (Houghton et al. 1990). Lindzen (1990) surmized that the value of ΔT_{2x} could be as low as 0.5 °C. Based on the observed temperature record, Schlesinger and Jiang (1991) found $\Delta T_{2x} = 1.2$ °C. But, as discussed by Wigley and Raper (1990), it is difficult to estimate ΔT_{2x} from the observed temperature record because of the unknown contribution from the climate's natural variability. $\Delta T_{2x} = 2.5$ °C is currently considered as the most likely estimate (Wigley and Raper, 1992; Hoffert and Covey, 1992). In the present study, calculations have been performed for climate sensitivities of 1.5, 2.5 and 4.5 °C, but results are only shown here for 2.5 °C (the best estimate case).

2.3 Sea Level Rise Model

The effects of global warming on sea level are determined by four processes: (i) thermal expansion of the ocean water, (ii) melting of mountain glaciers, (iii) ablation of the Greenland Ice Sheet, and (iv) ablation or accumulation of the Antarctic Ice Sheet (notably the West Antarctic Ice Sheet). The sea level model shown in Fig. 1 uses the calculated transient temperature changes to estimate sea level changes due to thermal expansion and melting ice.

For the calculation of the thermal expansion we use the thermal expansion coefficients from

Leyendekkers (1976). They depend on salinity and temperature. Vertical variations in thermal expansion are included explicitly in our model. The changes in the glacier volume and small ice caps are estimated according to Oerlemans (1989). With respect to the Greenland and Antarctic Ice Sheets, the dynamic response can be ignored for the time scale considered here. The static changes in the surface mass balance are modeled according to Warrick and Oerlemans (1990) and Oerlemans (1989).

3. Model Validation

In order to be able to assess the validity of the models and thus increase confidence in the calculated results, they must be compared to the observed data. A few examples are now shown to demonstrate the performance of the Muenster Model. A detailed description of this model and its validation is given by Jain and Bach (1992).

In Fig. 2 the observed values of the global mean surface air temperature related to 1880 (Houghton et al., 1990) are compared with the calculated values. The calculations are done for the presently accepted range of climate sensitivities of 1.5 to 4.5 °C for a doubling of CO_2. A value of 2.5 °C is currently considered as the most likely estimate. The calculated temperature curves are based on the effects of the fourteen greenhouse gases taken into account here. The observed curve incorporates not only all natural climatic variations but also all other possible additional anthropogenic influences. Overall, the clearly visible upward trends in the observed and calculated curves show a remarkable similarity. The model-calculated surface temperature changes in 1985, relative to 1860, are 0.42, 0.58, and 0.78 °C for the CO_2 doubling temperature sensitivities of 1.5, 2.5 and 4.5 °C respectively. This compares to an observed temperature rise of 0.6 °C ± 0.1 between 1880–1985 (Jones, 1988; Wigley et al., 1986).

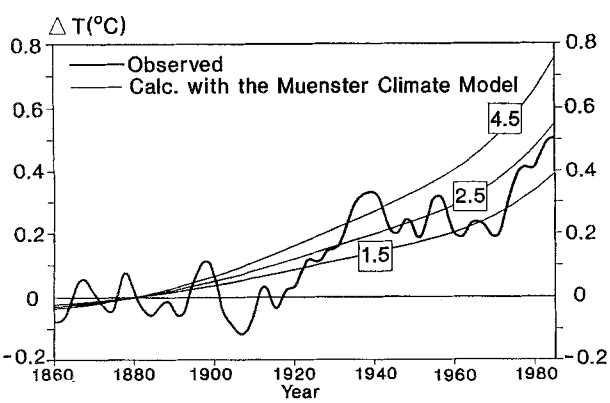


Fig. 2. Observed and calculated mean global surface temperature plotted in reference to 1880. The thick jagged line reflects the natural and additional man-made climatic effects. The thin continuous lines are based on the effects of 14 man-made greenhouse gases calculated with the Muenster Climate Model for model sensitivities of 1.5, 2.5 and 4.5 °C. The observed data are from Houghton et al. (1990)

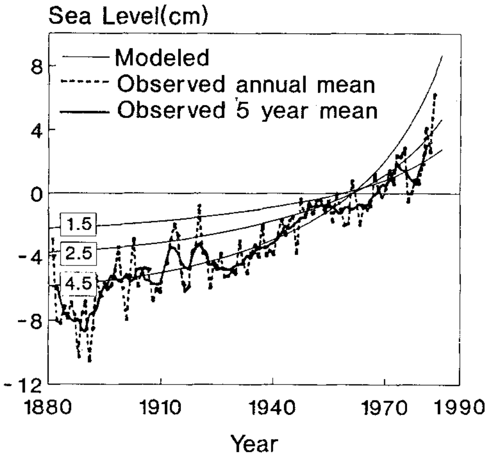


Fig. 3. Global mean sea level trend from tide-gauge data and comparison with the model-calculated mean sea level rise for climate sensitivities of 1.5, 2.5 and 4.5 °C. The base line is obtained by setting the average for the period 1951–1970 to zero. The observed data are from Gornitz and Lebedeff (1987)

Figure 3 compares the calculated mean sea level rise from 1880 to 1985 with the observed values shown as deviations from the 1951 to 1970 period (Gornitz and Lebedeff, 1987). The model-calculated mean sea level rise is slightly too low which may be due to the fact that the model does not take into account the internal variability of the climate system.

For the climate sensitivity range of 1.5 to 4.5 °C, the model-estimated sea level rise from 1860 to 1985 ranges from 4.6 to 10.1 cm, the major contributors being expansion (3.2–6.2 cm) and melting glaciers (1.4–3.9 cm). While snow accumulation in Antarctica contributes to a lowering of the sea level (0.17–0.31 mm), ablation in Greenland adds to the sea level rise (0.20–0.27 mm). Our estimated mean sea level rise is similar to that obtained by Oerlemans (1989) (ca. 9.5 cm from 1850 to 1985), and Gornitz et al. (1982) (ca. 10 cm from 1880 to 1980). According to present knowledge, the contribution of thermal expansion over the last hundred years was of the order of 2–6 cm (Wigley and Raper, 1987), and that of glacier retreat was 1.5–4.0 cm (Meier, 1984). Our findings are in good agreement with these values.

No doubt, 3-D models can reproduce changes in the climate system better than 1-D models because of their much more detailed modeling of the atmospheric processes and their feedbacks. 3-D climate model calculations require, however, a great deal of computer time and are thus very cost-intensive. Yet in order to increase the possibilities of consensus, decision-makers must be able to select from a large number of options. This can be best provided with the less costly 1-D climate models. It would be ideal, if the strengths of each of the two model hierarchies could be deployed in good scientific cooperation so as to work out reliable model results. This first of all requires that the results from the 1-D and 3-D climate models be compared with one another. For this comparison the same concentration input of the IPCC scenarios, the BAU and the "low" Dr (Houghton et al., 1990) were used to calculate the global mean transient temperature change from 1985 to 2085. The calculations were made with the 1-D Muenster Climate Model and the 3-D Hamburg Coupled Ocean-Atmosphere (O-A) Model (Cubasch et al., 1992). The atmospheric component of the coupled model is a low-resolution version of the forecast model of ECMWF (Hamburg GCM version, Fischer, 1987), and the oceanic component is the Hamburg Large-Scale Geostrophic Circulation Model described by Maier-Reimer and Mikolajewicz (1990). The Muenster Model calculations are made for a model sensitivity of 2.5 °C while the model sensitivity of the Hamburg Model is ca. 2 °C. Figure 4 shows for the low scenario Dr that the Muenster Model calculates a greater warming than the Hamburg Model over the entire period. In contrast, for the high scenario BAU the Hamburg values are lower than those of Muenster until about 2050, while thereafter the Hamburg values, in spite of their lower climate sensitivity, exceed those of Muenster. A plausible explanation for much of the delayed warming is the lack of the warm-up in the O-A 3-D model simulations for the period prior to 1985 (the experiment was started in 1985 from the equilibrium state rather than from an already warming state).

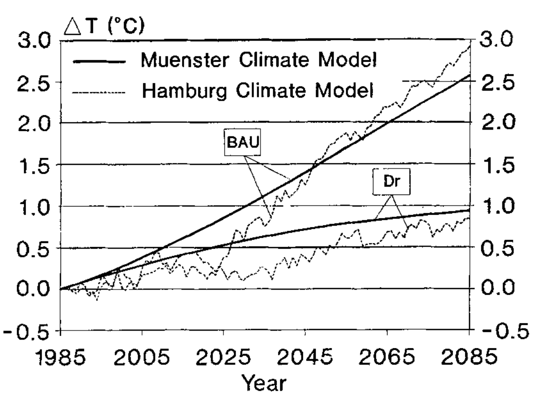


Fig. 4. Comparison of the global mean transient surface temperature changes (1985–2085) calculated with the 1-D Muenster Model and the 3-D Hamburg Model for the IPCC scenarios BAU and Dr. The climate sensitivity is 2.5 °C for the Muenster Climate Model and it is ca. 2 °C for the Hamburg Climate Model. The Hamburg data were supplied by Sausen (1991)

This type of model validation increases the confidence in the model calculations which are the only tools available for evaluating possible future trends and preventive measures. The various reduction measures are now examined for their effectiveness to reduce the climatic risks.

4. Scenario Analysis for Assessing the Effectiveness of Reduction Measures

4.1 Business-As-Usual (BAU)

The evaluation of the effectiveness of particular reduction measures requires a reference scenario. It is customary to use for this a so-called Business-As-Usual (BAU) scenario. The BAU scenario used here for reference is quite similar to Scenario IS92a of the Intergovernmental Panel on Climate Change (Leggett et al., 1992), except for the CFC values which are taken from the NASA (1992) data set. Table 1 summarizes the respective emission changes from 1990 to 2100 for the 12 greenhouse gases considered. By 2100 the CFCs and the halon are completely phased-out, and the CFCs are to a large extent substituted by the partially-halogenated HCFC-22. While CO_2 from fossil fuel burning and cement production experiences a more than threefold increase, CO_2 from forests is considerably reduced due to moderate forest destruction, and moderate biomass burning. In BAU forest clearing increases for the first few years and then declines steadily. Moderate esti-

Table 1. *Current and Projected Greenhouse gas Emission Estimates for Scenario Business-As-Usual (BAU) Corresponding to Scenario IS92a of the Intergovernmental Panel on Climate Change*

Greenhouse gas	Emission							Change (%)
	1990	2000	2005	2025	2050	2075	2100	1990–2100
CFC-11 (kt)[1]	289	168	137	94	85	16	2	−99
CFC-12 (kt)[1]	362	200	161	98	110	22	1	−100
CFC-113 (kt)[1]	147	29	22	21	24	0	0	−100
CFC-114 (kt)[1]	13	4	3	3	3	0	0	−100
CFC-115 (kt)[1]	7	5	4	1	1	0	0	−100
CCl_4 (kt)[1]	119	34	15	19	21	0	0	−100
CH_3CCl_3 (kt)[1]	738	353	137	97	110	0	0	−100
HCFC-22 (kt)[1]	138	275	329	568	1058	1232	1225	+788
H-1301 (kt)[1]	4	4	4	2	1	1	0	−100
CO_2 fr. forest destruct. + preserv. (Gt C)[2]	1.3	1.3	1.2	1.1	0.8	0.4	−0.1	−108
CO_2 from fossil fuels + cement (Gt C)[2]	6.2	7.2	8.0	11.1	13.7	19.9	20.4	+229
CH_4 (Mt)[2,3]	506.0	545.0	568.0	659.0	785.0	845.0	917.0	+61
N_2O (Mt N)[2,3]	12.9	13.8	14.8	15.8	16.6	16.7	17.0	+32
CO_2 equivalent (Gt C)[4]	12.2	12.2	12.7	15.7	18.7	20.2	26.3	+115

[1] Refers to the lastest (1989) estimated values taken from NASA (1992). [2] Corresponds to scenario IS92a of the IPCC (Houghton et al., 1992). [3] Includes both the anthropogenic and the natural components, the latter being 8 Mt of N for N_2O and 155 Mt for CH_4 in 1990 and staying constant thereafter. [4] Expresses all listed greenhouse gases in terms of CO_2 using for computation the 100-year Global Warming Potential (Houghton et al., 1992).

mates of carbon stored in the biomass are taken from OECD (1991). Toward 2100 emissions are slightly negative due to carbon sequestration by reforestation. The N_2O and CH_4 emissions include both the anthropogenic and the natural components leading by 2100 to an increase of about 30% and a 60%, respectively. Finally, the different gases are also expressed as CO_2 equivalents using for computation a 100 yr global warming potential. The combined greenhouse effect more than doubles in Scenario BAU from 1990 to 21000.

4.2 The Copenhagen Agreements for CFC, HCFC and Halon Reductions

In the 1980s the CFCs and halons contributed more than 20% to the additional man-made greenhouse effect (Ramanathan et al., 1987). Apart from the fact that a drastic CFC reduction is already necessary to protect the ozone layer, it is also a very effective measure for reducing greenhouse warming. The CFCs receive a good deal of attention, primarily because they have relatively long atmospheric lifetimes; i.e., they have relatively slow removal rates. Model calculations have shown that even if emissions of halogenated compounds were stopped immediately, the concentrations of these compounds would still remain at their current level for many years to come (Brühl and Crutzen, 1990). Moreover, the high greenhouse warming potential (Shine et al., 1990) provides another strong motive for the necessary of CFC control.

To control the CFCs and halons, a group of nations signed the Montreal Protocol in 1987. Soon it became clear, however, that it fell woefully short of adequately protecting the Earth's atmosphere. Therefore, further improvements became necessary, such as the London Agreements of 1990 and the Copenhagen Agreements of 1992 which resulted in further improvements by advancing the phase-out dates, above all, in the industrialized countries. Here we give only the reduction and phase-out dates for those substances which were used in this assessment. The new phase-out dates – all referring to January 1 – are (GECR, 1992; Gehring and Oberthur, 1993):

- for halon-1301 in 1994
- for the CFCs 11, 12, 113, 114 and 115 in 1996, with a 75% reduction set for 1994,
- for methyl chloroform (CH_3CCl_3) and carbon tetrachloride (CCl_4) in 1996, with a 50% cut in 1994 and an 85% cut in 1995, respectively,
- for HCFC-22 the cap begins in 1996 at a level

Table 2. *Current and Projected Greenhouse gas Emission Estimates for the Modified Scenario Climate Protection of the Enquete-Commission to the German Parliament (ECGP) and the CFC Modifications of the Copenhagen Agreement*

Greenhouse gas	Emission							Change (%)
	1990	2000	2005	2025	2050	2075	2100	1990–2100
CFC-11 (kt) [1]	335.3	39.3	20.7	0.0	stays zero thereafter			−100
CFC-12 (kt) [1]	427.2	30.9	21.4	0.0				
CFC-113 (kt) [1]	196.3	0.0	0.0	0.0				
CFC-114 (kt) [1]	13.8	0.0	0.0	0.0				
CFC-115 (kt) [1]	14.0	0.0	0.0	0.0				
CCl_4 (kt) [1]	151.9	0.0	0.0	0.0				
CH_3CCl_3 (kt) [1]	540.3	0.0	0.0	0.0				
HCFC-22 (kt) [1]	147.5	191.7	189.8	37.9				
Halon-1301 (kt) [1]	10.2	2.7	1.2	0.06				
CO_2 from forest destruction/preserv. (Gt C)[2]	2.4	2.3	1.2	−0.2	−0.5	0.0	0.0	−100
CO_2 from fossil fuels and cement (Gt C)[3]	6.2	6.2	5.8	4.6	2.9	2.3	1.7	−72
CH_4 (Mt)[2,4]	506.0	556.6	581.9	637.5	607.2	556.6	480.7	−5
N_2O (Mt N)[2,4]	12.9	13.8	14.1	14.4	12.9	9.7	6.5	−50
CO_2 equivalent (Gt C)[5]	12.3	11.0	9.4	7.0	4.8	4.4	3.4	−72

[1] Refers to the latest (1989) estimated values taken from NASA (1992). [2] ECGP (1990). [3] ECGP (1991) modified (see text). [4] Includes both the anthropogenic and the natural components, the latter being 8 Mt of N for N_2O and 155 Mt for CH_4 in 1990 and staying constant thereafter. [5] Expresses all listed greenhouse gases in terms of CO_2 using for computation the 100-year Global Warming Potential (Houghton et al., 1992).

equal to each party's ODP-weighted 1989 HCFC use plus 3.1% of its 1989 ODP-weighted CFC consumption,

- the cap of HCFC-22 is followed by cuts of 35% by 2004, 65% by 2010, 90% by 2015, 99.5% by 2020, and a phase-out by 2030 with a 0.5% production "tail" extending for 10 years to permit the continued servicing of HCFC chillers.

The schedule for the production phase-out and the resulting emission reduction is shown in Table 2.

4.3 The Tropical Forest Preservation Plan for CO_2 Reduction

CO_2 emission from the destruction of tropical forests contributed ca. 12% to the additional man-made greenhouse effect in the 1980s (ECGP, 1990). Apart from the fact that a drastic reduction is already called for on grounds of preserving the tropical forest ecosystems and the living space of the indigenous peoples, it would also lower the greenhouse effect.

In order to assess the effectiveness of emission reduction measures we examine here the following three versions of tropical forest destruction and one version of tropical forest preservation:

- In the first destruction version a forest area of ca. 440,000 km^2 (or 157,000 sq. miles) is destroyed annually up to complete destruction in 2030.
- In the second version ca. 300,000 km^2 (or 115,000 sq. smiles) are completely destroyed by 2050.
- In the third version ca. 200,000 km^2 (or 77,000 sq. miles) are completely destroyed by 2100.
- The tropical forest preservation plan of the Enquete-Commission (ECGP, 1990) envisages in the first stage a reduction of the forest destruction rate between 1990 and 2000 to that of 1980; in the second stage destruction is stopped by 2010 so that the total forest area in absolute terms no longer declines; and in the third stage from 2010 to 2030 the forest stands are restored to their 1980 size.

The emission changes of the forest destruction and preservation schemes are shown in Fig. 5.

4.4 The Energy-Related CO_2 Reductions

The energy-related CO_2 emission is the greatest contributor to the additional man-made green-

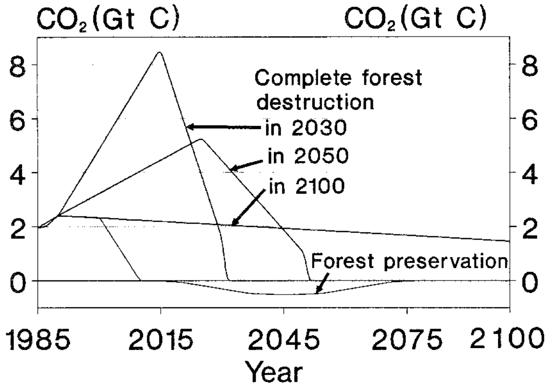


Fig. 5. Global CO_2 emission due to various forest destruction schemes and the forest preservation plan of the Enquete-Commission of the German Parliament

house effect. In the 1980s the contribution amounted to ca. 37% of the total man-made greenhouse effect (ECGP, 1991). Thus, the energy sector (including transportation) becomes the most decisive factor in the greenhouse reduction strategy.

Here we consider for energy-related CO_2 emission two scenarios: The Business-as-Usual Scenario (Table 1) which is essentially the same as the IPCC IS92a Scenario (Leggett et al., 1992), and the Climate Protection Scenario, which was developed by us for the Enquete-Commission and published in their reports as Scenario D (e.g. ECGP, 1991). Not only the recent political and economic developments, but also the reluctant reduction commitments by the nations of the world at the UNCED in Rio de Janeiro and in the subsequent months, prompted us to modify the energy-related CO_2 emissions in the original Climate Protection Scenario (Table 2), and to develop a more differentiated country allocation system with more appropriate reduction targets.

Past experience has shown that undifferentiated targets, such as the 20% CO_2 emission reduction for the world as a whole, as recommended by the Toronto Climate Conference in 1988 and repeated by the Second World Climate Conference in 1990 in Geneva, do not spur any action. Such global statements are of little use. Similarly, a burden allocation to individual countries is also not very feasible. The secret of a successful greenhouse gas policy is rather a fair burden sharing among comparable groups of countries, taking due account, among others, of such factors as the socio-economic, demographic, and technological potential. (Bach and Jain, 1991, 1992, 1992–1993).

To arrive at a tractable grouping of the world's countries, we have relied on the following tentative list of criteria (Krause, Bach and Koomey, 1990; ECGP, 1991; Bach and Jain, 1992 and 1992–1993):

- CO_2 emission by amount, per capita and cumulated,
- economic indicators (per capita GNP, debt, world trade),
- resources, production and consumption of energy,
- energy efficiency,
- population, migration and refugee developments,
- others (such as CO_2 emission per unit of land, consideration of sinks, climatic impacts, and principles of fairness, equity and responsibility, etc.).

Our procedure to group the world's 179 countries (1987) is as follows: We use information on the above criteria together with subjective political judgement to allocate all countries to one of six groups (Table 3A). We then test the subjective selection method with objective statistical methods using a combination of discrimination and cluster analyses (Bach and Jain, 1992). Using a cut-off emission level of >10 Mio t of CO_2 we finally arrive at 69 countries to be allocated to the six groups amounting to about 98% of the total global 1987 CO_2 emission. This is very good news, because the reduced number of actors should enormously facilitate the upcoming negotiations. The break-up of many countries into smaller entities since 1987 has, however, been taken into account when developing the reduction targets.

The reduction depends on the ultimate objective, which according to the Framework Convention on Climate as signed at the UNCED in Rio in 1992, is (INC, 1992):

- ... "the stabilization of greenhouse gas concentrations in the stratosphere at a level that would prevent dangerous anthropogenic interference with the climate system", and
- "such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

This definition is in full accord with that of the

Table 3. *Allocation of CO_2 Emission (>10 Mt/yr) to six Groups of Countries on the Basis of "Political" Judgement as well as Cluster and Discrimination Analysis, 1987. B. Allocation of CO_2 Emission Targets in Percent Changes Relative to 1987 to six Groups of Countries for Scenario Climate Protection (which is a modified version of Scenario D of the Enquete-Commission of the German Parliament, ECGP, 1990)*

A. Allocation of CO_2 emission to groups of countries (Mio t)

Industrialized countries (ICs) – Economically: Strong		Less strong		Weak		Total ICs	Arabic oil-producing countries		Countries in transition		Developing countries (DCs)				World total
1 USA	5021	1 Spain	186	1 FUSSR	3841		1 Saudi Africa	161	1 South Africa	323	1 China	2175	13 Malays.	41	
2 Germany	1067	2 Greece	67	2 Poland	485		2 Iran	137	2 South Korea	186	2 India	554	14 Nigeria	36	
3 Japan	963	3 Portugal	32	3 F. Czech.	244		3 Algeria	48	3 Argent.	141	3 Mexico	298	15 Cuba	34	
4 U.K.	625	4 Ireland	30	4 Romania	225		4 United Arab Emir.	46	4 Israel	29	4 Brazil	202	16 Philipp.	32	
5 Canada	456	5 New Zealand	24	5 F. Yugosl.	129		5 Iraq	33	5 Singap.	26	5 North Korea	151	17 Syria	28	
6 Italy	429			6 Bulgaria	109		6 Kuwait	28	6 Trinidad	13	6 Turkey	135	18 Chile	23	
7 France	388			7 Hungary	87		7 Libya	25			7 Indon.	103	19 Peru	23	
8 Australia	257						8 Bahrain	12			8 Venez.	96	20 Morocc.	20	
9 Netherlands	196						9 Quatar	12			9 Egypt	23	21 Vietn.	19	
10 Belgium	114						10 Oman	10			10 Thail.	60	22 Zimbab.	15	
11 Denmark	65										11 Pakist.	54	23 Ecuad.	13	
12 Austria	60										12 Colomb.	49	24 Banglad.	12	
13 Sweden	58												25 Tunisia	12	
14 Finland	55														
15 Switzerland	43														
16 Norway	36														
Total (47%)	9833	Total (2%)	339	Total (25%)	5120	(74%) 15292	Total (2%)	511	Total (4%)	718			Total (20%)	4258	(98.1%) 20779

B. Allocation of CO_2 emission targets (%)

Year	Strong	Less strong	Weak	Total ICs	Arabic oil-producing countries	Countries in transition	Developing countries (DCs)	World total
1981[1]	+3	+7	+5	+4	+7	+6	+3	+4
1989[1]	+5	+17	+1	+4	+15	+6	+11	+6
1990[1]	+8	+35	−5	+4	+25	+10	+17	+8
1995	+5	+32	−5	+2	+45	+25	+50	+15
2000	−9	+20	0	−5	+25	+15	+50	+8
2005	−25	0	+2	−15	+10	+10	+50	0
2020	−40	−15	−10	−30	−5	−5	+35	−15
2050	−80	−70	−60	−73	−60	−55	+32	−50
2075	−85	−85	−65	−78	−63	−60	+5	−60
2100	−90	−80	−70	−83	−70	−65	−25	−70

[1] Observed development (UN, 1991).
Bach and Jain (1992–1993)

Enquete-Commission (ECGP, 1989), which has stipulated that the required emission reductions depend on:

- the desired climate and ecosystem protection which is defined as the mean global rate of surface temperature change of 0.1 °C per decade between 1990 and 2100, which, together with the already experienced warming of about 0.6 °C since 1860, leads to a mean global warming ceiling of ca. 2 °C by 2100 as compared to 1860; such a warming limit was also endorsed by the 1987 Villach Climate Conference and by both the German Physical and the German Meteorological Societies;
- the number of considered greenhouse gases (the reduction options increase and the required reduction shares decrease, if, besides CO_2, also the other important greenhouse gases* are taken into account);
- the time period and the reference level (the required reduction quota can obviously vary considerably depending on whether a certain reduction is to be reached in 2020 as compared to 1990 or already in 2005 relative to 1987);
- other political requirements and priorities.

On the basis of these definitions a tractable scheme of emission targets can be set up. Our procedure for CO_2 is as follows: The global CO_2 emission targets for specified years are determined with the help of the Muenster Climate Model discussed above. These global changes are then allocated on the basis of the criteria presented above to the respective groups of countries shown in Table 3A.

The following significant results emerge from Table 3B:

- From 1987 to 1990 considerable CO_2 emission growth has taken place in almost all groups of countries and worldwide, except in the economically weak group of industrialized countries (ICs) where the transition from a planned to a market economy resulted in some reduction not by design but rather as part of the difficult adaptation process.
- In light of this growth, the pent-up demand in the developing world, and the reluctance to make any firm and decisive reduction commitments as documented in Rio, the Toronto goal of a world-wide 20% CO_2 reduction by 2005 relative to 1988 is quite unrealistic.
- A global return in 2005 to the 1987 value would require a major reduction effort of the order of 25%, especially on the part of the economically strong ICs.
- The stabilization of CO_2 concentration in the atmosphere stipulated by the UNCED would require a CO_2 emission reduction of at least 80% by the economically strong ICs and 50% worldwide.
- The desired climate and ecosystem protection (i.e. a 2 °C global warming ceiling and a 0.1 °C/decade limit) require in addition to the CO_2 reduction by 2100 a 100% reduction both of the CFCs, HCFCs, halons and CO_2 from forest destruction as well as a 50% reduction of N_2O and a 5% reduction of CH_4 (Table 2).

The required CH_4 and N_2O reduction rates are discussed next.

4.5 The CH_4 and N_2O Reductions

Assessing future trends in atmospheric CH_4 and N_2O concentrations require better knowledge of sources and sinks of these two gases. The individual sources of atmospheric CH_4 and N_2O have been qualitatively identified (e.g. Asscheleyn et al., 1993), but there are significant uncertainties in the magnitude of their strengths. Human activities such as rice cultivation, biomass burning, and natural gas venting (coal mining, oil drilling) and leakage have increased in output of CH_4, and these combined with an apparent decrease in the concentration of tropospheric OH, yield the observed rise in global CH_4. However, the quantitative importance of each of the factors contributing to the observed increase is not well known at present (Watson et al., 1990). In the case of N_2O, the sum of all known anthropogenic and natural sources is still barely sufficient to balance the calculated atmospheric concentration (Watson et al., 1992). It is therefore very difficult to develop meaningful scenarios. Both are important greenhouse gases. In the area of energy and transport the contribution of CH_4 to the additional greenhouse effect is about 5%. A larger contribution

* We include in our model calculations 14 of the most important greenhouse gases, such as CO_2, CH_4, CFC 11, 12, 113, 114, 115, HCFC 22, H 1301, CH_3CCl_3, CCl_4, O_3 in the troposphere and H_2O in the stratosphere (Piehler, Bach and Jain, 1991).

comes from agriculture (mainly rice paddy fields and feedlots), and, together with N_2O and CO, another 6% is contributed through the destruction of tropical forests. In the area of agriculture (artificial fertilization), N_2O contributes about 4% to the additional greenhouse effect. The N_2O contribution from tropical forest destruction and savanna fires is assumed to be substantial, but it is currently also highly uncertain. At any rate it is important to include these two gases in the measures to mitigate the additional greenhouse effect.

To this end we consider two different scenarios, i.e. one with the continuation of the present trend (BAU), and other one with reductions. Scenario BAU leads to an emission increase of 61% for CH_4 and 32% for N_2O over the period 1990 to 2100 (Table 1) (Leggett et al., 1992). The reduction scenario is based on the following time table of assumed emission changes (Bach and Jain, 1992–1993):

- For CH_4 there are annual increases of 1% from 1990 to 2000, 0.9% from 2001 to 2005, and 0.4% from 2006 to 2025; and there are annual decreases of 0.2% from 2026 to 2050, 0.3% from 2051 to 2075, and 0.5% from 2076 to 2100.
- The emission of CO necessary for calculating the CH_4 cycle follows the same pattern of changes. From 1990 to 2025 the OH concentration has been decreasing considerably because our assumption is that of a low ambient NOx concentration which involves a decreasing OH concentration in the case of increasing CO and CH_4 concentration (and vice versa after 2025).
- For N_2O there are annual increases of 0.7% from 1990 to 2000, 0.5% from 2001 to 2005, and 0.1% from 2006 to 2025; but there are annual decreases of 0.5% from 2026 to 2050, 1% from 2051–2075, and 1.3% from 2076 to 2100.

Due to the quite different atmospheric lifetimes of CH_4 (ca. 10 years) and N_2O (ca. 150 years), CH_4 responds much more quickly to any reduction measures in CO and CH_4 emissions.

5. Are these Reduction Measures Sufficient for Climate Protection?

The emission reductions due to the four packages of measures result in concentration and temperature changes. This is shown in the two final sections. By starting with BAU and subtracting the effected reduction of each package of measures, it can be investigated whether the considered measures suffice to achieve the desired climate protection.

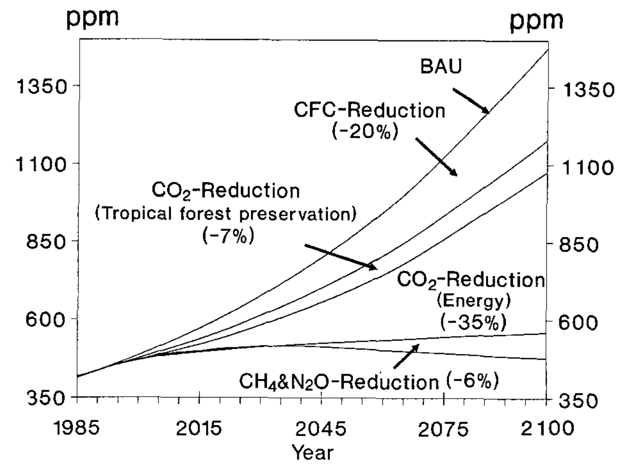


Fig. 6. Effectiveness of the different measures for the reduction of atmospheric concentrations given in terms of the equivalent CO_2 concentration. The calculations were made with the Muenster Climate Model. The percent values give the contribution of the respective measures to the reduction of the equivalent CO_2 concentration in 2100 as related to BAU

5.1 The Effect of the Reduction Measures on the Equivalent CO_2 Concentration

Due to the different greenhouse potentials of the various greenhouse gases it is necessary, for reasons of comparison, to express them as equivalents of the CO_2 concentration. The following important results may be derived from Fig. 6 for target year 2100 starting with Scenario BAU (i.e. no decisive measures):

- Reducing the CFC, HCFC, and halon emissions by strengthening the Montreal Protocol as laid down in the London and Copenhagen Agreements would lower the equivalent CO_2 concentration by ca. 20%.
- The three-stage Enquete-Commission plan for preserving the tropical forests would lead to a further 7% reduction.
- The energy-related CO_2 emission reduction targets of the modified Climate Protection Scenario of the Enquete-Commission would result in the most decisive reduction of the equivalent CO_2 concentration with an additional 35%.

- The CH_4 and N_2O reduction scenarios together contribute another 6% to the overall reduction.
- In comparison to BAU, all measures combined effect a substantive 68% reduction by 2100.
- While it is true that the 2100 equivalent CO_2 concentration is still ca. 6% above the 1990 level, it is more important to state that, as a result of the measures, the concentration begins to fall after 2035.

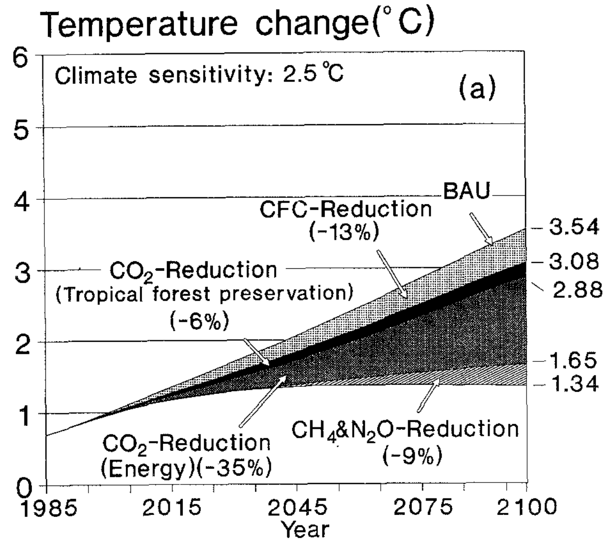
It finally remains to be examined, whether these considerable concentration reductions are sufficient to achieve the desired climate protection and a limitation to sea level rise.

5.2 The Effect of the Reduction Measures on Global Warming and Sea Level Rise

The effectiveness of the individual packages of measures to reduce the mean global temperature is now summarized for the currently accepted climate sensitivity range of 2.5 °C (1.5°–4.5 °C) for a CO_2 doubling. The mean global warming would increase to:

- 3.5 °C (2.4–5.0), if current trends continued (Scenario BAU). The mean global temperature could be reduced by the packages of measures as follows:
- from 3.5 °C (2.4–5.0) to 3.1 °C (2.1–4.4), or ca. 12% by following the phaseout plan for CFCs, HCFCs and halons of the Copenhagen Agreement;
- from 3.1 °C (2.1–4.4) to 2.9 °C (2.0–4.1), or about 6% by carrying out the tropical forest preservation plan of the Enquete-Commission of the German Parliament;
- from 2.9 °C (2.0–4.1) to 1.6 °C (1.1–2.4), or about 35% through measures of the modified Scenario Climate Protection of the Enquete-Commission;
- from 1.6 °C (1.1–2.4) to 1.3 °C (0.9–2.0), or ca. 9% through the CH_4 and N_2O Reduction Scenario.

Finally, the question posed in this paper can be answered in the affirmative: The four packages of measures could keep the mean global transient warming below a ceiling of 2 °C even at the highest considered climate sensitivity of 4.5 °C. Details of the effectiveness of the reduction measures are shown for the most likely climate sensitivity of 2.5 °C for temperature in Fig. 7a and for sea level in Fig. 7b.



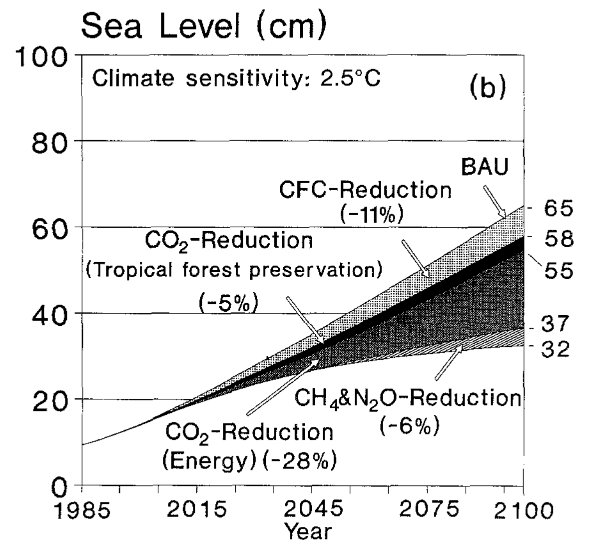


Fig. 7. Effectiveness of the different measures to mitigate the additional man-made greenhouse effect. The temperature (a) and mean sea level rise (b) changes are calculated with the Muenster Climate Model for a climate sensitivity of 2.5 °C, and are related to the preindustrial value of 1860. The percent values give the contribution of the respective measures to the temperature and sea level rise reductions in 2100

6. Conclusions

The main conclusions of this paper can be summarized as follows:

- The Muenster Climate Model is a powerful tool in that it permits to relate the science and policy aspects of the greenhouse effect. Very importantly it allows one to derive sets of permissible emission targets for a desired climate protection. Moreover, it enables scientists working in the field of climatic change to develop a more policy-oriented perspective.

- Continuation of present greenhouse gas emission trends leads to a rapid global temperature and sea level rise. This can only be controlled by the timely adoption of feasible reduction measures.
- Of all the emission reduction measures for mitigating the additional greenhouse effect, those for the CFCs, HCFCs, and halons are considered to be the most cost-effective and the most conducive to political enforcement. Strengthening the Montreal Protocol through the London and Copenhagen Agreements could bring considerable relief to the climate. A poll at the November 1993 Fifth Meeting of the Parties to the Montreal Protocol showed that so far only 9 countries had ratified the Copenhagen Amendments (GECR, 1993). For these amendments to come into force on schedule, 20 ratifications are required by January 1, 1994. Besides reducing global warming, all of these measures are necessary to protect the stratospheric ozone layer.
- The tropical forest preservation plan recommended by the Enquete-Commission of the German Parliament can make a contribution to the reduction of atmospheric CO_2 emissions by reducing forest destruction and by introducing reforestation programs in the first half of the 21st century. But this contribution to mitigating the additional greenhouse effect is relatively small, when it is related to 2100, the model calculations' final year. Conservation of the tropical forests nevertheless demands a very high priority both on ecological groups and for reasons to preserve the living space for indigenous peoples.
- The reduction of the energy-related CO_2 release is by far the most effective measure for mitigating the man-made greenhouse effect and should therefore have a very high priority. The best results are to the expected from industrialized countries with the highest economic power and the greatest technical know-how. Technical and economic aid can also help activate relatively quickly the great potential for reduction in other countries.
- The emission reduction potential of the greenhouse gases CH_4 and N_2O has not yet been investigated by us in detail. But according to our preliminary estimates, CH_4 could in the short term make a sizeable contribution to reduce the greenhouse effect, as could N_2O in the medium and long term. Predicting the global trends in CH_4 requires an understanding of the chemical interactions of emissions of CO, NOx, OH on a regional scale, as well as of the transport of O_3 between its source regions and the remote troposphere. A global average model of the sort used in this study cannot take into account such regional effects. To simulate these, 2- or 3-dimensional models are needed. Therefore, our objective is to develop a 2-D model that can be used to explore the effects on the climate system in more detail.

Finally, all four packages of measures taken together could reduce the additional man-made greenhouse effect by about 60% until 2100, i.e. over the climate sensitivity range of 2.5 °C (1.5–4.5) for a CO_2 doubling from

- 3.5 °C (2.4–5.0) without specific measures to
- 1.3 °C (0.9–2.0) with the above packages of measures.

At the same time the mean global sea level rise could be lowered from

- 65 cm (46–88) without specific measures to
- 32 cm (22–47) with the above packages of measures.

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References

Asscheleyn, P. H., Delaune, R. D., Patrick, W. H., 1993: Methane and nitrous oxide emissions from laboratory measurements of rice soil suspension – effect of soil oxidation-reduction status. *Chemosphere*, **26** (25 N1–4), 251–260.

Bach, W., Jain, A. K., 1990: The CFC greenhouse potential of scenarios possible under the Montreal protocol. *Int. J. Climatology*, **10**, 439–450.

Bach, W., Jain, A. K., 1991: Toward climate conventions: Scenario analysis for a climate protection policy. *Ambio*, **20**, 322–329.

Bach, W., Jain, A. K., 1992: Climate and ecosystem protection requires burden sharing. The specific tasks after Rio (I). *Perspectives in Energy*, **2**, 67–93.

Bach, W., Jain, A. K., 1992–1993: Climate and ecosystem protection requires binding emission targets. The specific tasks after Rio (II). *Perspectives in Energy,* **2**, 173–214.

Brühl, C., Crutzen, P. J., 1990: Ozone and climate changes in the light of the Montreal protocol: A model study. *Ambio,* **19** (6–7), 293–301.

Cubasch, U., Hasselmann, K., Hock, H., Maier-Reimer, E., Mikolajewicz, U., Santer, B. D., Sausen, R., 1992: Time dependent greenhouse warming computations with a coupled ocean-atmosphere model. *Climate Dynamics,* **8**, 55–69.

ECGP (Enquete Commission of the German Parliament), 1989: *Protecting the Earth's Atmosphere. An International Challenge.* Bonn, Karlsruhe: Economica and C. F. Müller, 592 pp.

ECGP, 1990: *Protecting the Tropical Forests. A High-Priority International Task.* 2nd Report. Bonn, Karlsruhe: Economica and C. F. Müller, 968 pp.

ECGP, 1991: *Protecting the Earth. A Status Report with Recommendations for a new Energy Policy.* 3rd Report, 2 vols. Bonn, Karlsruhe: Economica and C. F. Müller, 1680 pp.

Fischer, G., 1987: *Climate simulations with the ECMWF T21-model in Hamburg.* Hamburg: Meteorologisches Institut, Large Scale Atmospheric Modelling Report No. 1, 159 pp.

Gamlen, P. H., Lane, B. C., Midgley, P. M., Steed, J. M., 1986: The production and release to the atmosphere of CCl_3F and CCl_2F_2 (chlorofluorocarbons CFC-11 and CFC-12). *Atmos. Environ.,* **20**, 1077–1085.

Gehring, T., Oberthur, S., 1993: The Copenhagen meeting. *Environment Policy and Law,* **23/1**, 6–12.

Global Environmental Change Report (GECR), 1992: *The new Ozone Accord: The Strongest Packages of law but not enough.* **Vol. IV**, No. 23, 1–3 (4 December 1992).

Gornitz, V., Lebedeff, S., 1987: Mean sea level changes during the past century, In: Nummedal, D., Pilkey, O. H., Howard, J. D. (eds): *Sea Level Fluctuations and Coastal Evolution.* SEPM special Publication No. **41**.

Gornitz, V., Lebedeff, S., Hansen, J., 1982: Global sea level trend in the past century. *Science,* **215**, 1611–1614.

Hammitt, J. K., Camm, F., Connell, P. S., Mooz, W. E., Wolf, K. A., Wuebbles, D. J., Bamezai, A., 1987: Future emission scenarios for chemicals that may deplete stratospheric ozone. *Nature,* **330**, 711–716.

Harvey, L. D. D., Schneider, S. H., 1985: Transient climate response to external forcing on 10^0–10^4 year time scales. Part I: Experiments with globally-averaged coupled atmosphere and ocean energy balance models. *J. Geophys. Res.,* **90**, 2191–2205.

Harvey, L. D. D., 1989a: Effect of model structure on response of terrestrial biosphere models to CO_2 and temperature increases. *Global Biogeochem. Cycles,* **3**, 137–153.

Harvey, L. D. D., 1989b: Managing atmospheric CO_2. *Climatic Change,* **15**, 343–381.

Hauglustain, D. A., Garnier, C., Brasseur, G. P., Megie, G., 1994: The importance of atmospheric chemistry in the calculation of radiative forcing on the climate system. *J. Geophys. Res.* (accepted).

Hoffert, M. I., Covery, C., 1992: Deriving global climate sensitivity from paleoclimate reconstructions. *Nature,* **360**, 573–576.

Hoffert, M. I., Wey, Y. C., Callegari, A. J., Broecker, W. S., 1979: Atmospheric response to deep-sea injections of fossil fuel carbon dioxide. *Climatic Change,* **2**, 53–68.

Houghton, J. T., Callander, B. A., Varney, S. K. (eds.), 1992: *Climate Change: The Supplementary Report to the IPCC Scientific Assessment.* Cambridge: University Press, 200 pp.

Houghton, J. T., Jenkins, G. J., Ephraums, J.-J. (eds.), 1990: *Climatic Change: The IPCC Scientific Assessment.* Cambridge: University Press, 364 pp.

Jain, A. K., Bach, W., 1993: Theory and development of an integrated climate model. Ace-report No. 66, Univ. of Muenster, Germany, 39 pp.

Jones, P. D., 1988: The influence of ENSO on global temperature. *Climate Monitor,* **17**(3), 80–89.

INC (Intergovernmental Negotiating Committee), 1992: *Report of the INC for a Framework Convention on Climate Change on the work of the second part of the 5th session,* held at New York from April 30 to May 9, 1992. New York.

Krause, F., Bach, W., Koomey, J., 1990: *Energy Policy in the Greenhouse. From Warming Fate to Warming Limit.* London: Earth Scan Pub.

Leggett, J., Pepper, W. J., Swart, R. J., 1992: Emission scenarios for IPCC: An update. In: Houghton, J. T., Callander, B. A., Varney, S. K. (eds.) *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment.* Cambridge: University Press, 69–96.

Lelieveld, J., Crutzen, P. J., 1992: Indirect chemical effects of methane on climate warming. *Nature,* **355**, 339–342.

Levine, J. S., Rinsland, G. P., Tennille, G. M., 1985: The photochemistry of methane and carbon monoxide in the troposphere in 1950 and 1985. *Nature,* **318**, 254–257.

Leyendekkers, J. V., 1976: *Thermodynamics of Sea Water.* New York: Dekker, 262–304.

Lindzen, R. S., 1990: Some coolness concerning global warming. *Bull. Amer. Meteor. Soc.,* **71**, 288–299.

Meier, M. F., 1994: Contribution of small glaciers to global sea level. *Science,* **226**, 1418–1421.

Meier-Reimer, E., Mikolajewicz, U., 1990: Experiments with an OGCM on the causes of the Younger Dryas. In: Ayala-Castanares, A., Wooester, W., Yanez-Arancibia, A. (eds.) *Oceanography 1988.* Mexico City: UNAM Press, 87–100.

NASA, 1992: *Concentrations, Lifetimes and Trends of CFCs, Halons, and Related Species.* Washington, D. C.: NASA-Report.

OECD (Organization for Economic Cooperation and Development), 1991: *Estimates of Greenhouse Gas Emissions and Sinks.* Paris: Final report from the OECD experts meeting, OECD experts meeting, Paris, 18–21 February, 1991.

Oerlemans, J., 1989: A projection of future sea level. *Climatic Change,* **15**, 151–174.

Oeschger, H., Siegenthaler, U., Schotterer, V., Gugelmann, A., 1975: A box diffusion model to study the carbon dioxide exchange in nature. *Tellus,* **27**, 168–192.

Piehler, H., Bach, W., Jain, A. K., 1991: *The Muenster Climate Model. Concept and Demonstration. Ace-report No. 49,* Univ. of Muenster, 94 pp.

Ramanathan, V., Callis, L., Cess, R. D., Hansen, J., Isaksen, I. Kuhn, W., Lacis, A., Luther, F., Mahlman, J., Reck, R., Schlesinger, M., 1987: Climate-chemical interactions and effects of changing atmospheric trace gases. *Rev. Geophys.*, **25**, 1441–1482.

Rind, D., Lacis, A., 1993: The role of the statosphere in climate change. *Surveys in Geophysics*, **14**, 133–165.

Rotmans, J., Swart, R. J., Vrieze, O. J., 1990: The role of CH_4–CO–OH cycle in the greenhouse problem. *The Science of the Total Environment*, **94**, 233–252.

Sausen, R., 1991: Personal communication.

Schlesinger, M. E., Jiang, X., 1991: Revised projection of future greenhouse warming. *Nature*, **350**, 219–221.

Shine, K. P., Derwent, R. G., Wuebbles, D. J., Morcrette, J. J., 1990: Radiative forcing of climate. In: Houghton, J. T., Jenkins, G. J., Ephraums, J.-J. (eds.) *Climatic Change: The IPCC Scientific Assessment*. Cambridge: University Press, 41–68.

UN (1991): *Energy Statistics Yearbook*. New York: Dept. of Int. Economic and Social Affairs.

Vaghjiani, G. L., Ravishankara, A. R., 1991: New measurements of the rate coefficient for the reaction of OH with methane. *Nature*, **350**, 406–409.

Warrick, R. A., Oerlemans, H., 1990: Sea level rise. In: Houghton, J. T., Jenkins, G. J., Ephraums, J.-J. (eds.) *Climatic Change: The IPCC Scientific Assessment*. Cambridge: University Press, 257–282.

Watson, R. T., Rodhe, H., Oeschger, H., Siegenthaler, U., 1990: Greenhouse gases and aerosols. In: Houghton, J. T., Jenkins, G. J., Ephraums, J.-J. (eds.) *Climatic Change: The IPCC Scientific Assessment*. Cambridge: University Press, 1–40.

Watson, R. T., Meira Filho, L. G., Sanhueza, E., Janetos, A., 1992: Sources and sinks. In: Houghton, J. T., Challander, B. A., Varney, S. K. (eds.) Climate Change 1992: *The Supplementary Report to the IPCC Scientific Assessment*. Cambridge: University Press, 25–46.

Wiley, T. M. L., 1987: Relative contributions of different trace gases to the greenhouse effect. *Climate Monitor*, **16**(1), 14–28.

Wigley, T. M. L., Raper, S. C. B., 1987: Thermal expansion of sea water associated with global warming. *Nature*, **330**, 127–131.

Wigley, T. M. L., Jones, P. D., Kelly, P. M., 1986: Warm world scenarios and the detection of climatic change induced by radiatively active gases. In: Bolin, B., Döös, Bo, R., Jäger, J., Warrick, R. A. (eds.) *The Greenhouse Effect, Climatic Change, and Ecosystems*. Scope 29, Chichester: John Wiley, 271–321.

Wigley, T. M. L., Barnett, T. P., 1990: Detection of greenhouse effect in the observations. In: Houghton, J. T., Jenkins, G. J., Ephraums, J.-J. (eds.) *Climatic Change: The IPCC Scientific Assessment*. Cambridge: University Press, 239–256.

Wigley, T. M. L., Raper, S. C. B., 1990: Natural variability of the climate system and detection of the greenhouse effect. *Nature*, **344**, 324–327.

Wigley, T. M. L., Raper, S. C. B., 1992: Implications for climatic and sea level of revised IPCC emission scenarios. *Nature*, **357**, 293–300.

Wuebbles, D. J., Tamaresis, J. S., 1993: The role of methane in the global environment. In: Khali, M. A. K. (ed.) *Atmospheric Methane: Sources, Sinks, and Role in Global Change*. NATO ASI Series, Vol. 13. Berlin: Springer, 469–513.

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