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A simple model for scenario studies of changes in global climate

Version 1.0

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Abstract

This paper gives a documentation of a simple climate model for studying the effects of future climate gas emissions on global mean temperature and sea level. Input to the model is global emissions of 29 gases. Atmospheric concentration of carbon dioxide (CO₂) is calculated on the basis of work published by Joos et al. (1996).

The parameterisation is founded on complex models for the carbon cycle where the exchange of carbon between the atmosphere, the biosphere and the oceans is considered. Future concentrations of other gases are calculated by standard equations based on emissions and chemical decay of the different gases in the atmosphere. Radiative forcing from the modelled concentrations in source gases is calculated by applying standard parameterisations published in the literature. In addition, radiative forcing is calculated for soot and sulphate aerosols (direct and indirect effects) as well as the secondary components tropospheric and stratospheric ozone and stratospheric water vapour.

The estimated radiative forcing serves as input to an energy-balance-climate/upwelling-diffusion-ocean model developed by Professor Michael E. Schlesinger (Schlesinger et al., 1992). The global and hemispherical change in annual mean temperature is calculated based on the exchange of energy between the atmosphere and the oceans, and the transport of energy in the ocean. The model uses prescribed values for climate sensitivity based on GCM results. The change in sea level rise is both determined by the melting of glaciers and the thermal expansion of the ocean.

The model is similar to those applied by IPCC for scenario studies (IPCC, 1996 p 316-318; IPCC, 1997; Wigley and Raper, 1992). Presently, the model serves as a useful tool in the analysis of possible global climatic changes caused by present and future greenhouse gas emissions. However, the intention is to extend the model so that regional predictions of temperature and other climate variables can be carried out.

Acknowledgements

We thank Professor Michael Schlesinger for kindly giving us a copy of his energy-balance-climate/upwelling-diffusion-ocean (EBC/UDO) model, Professor Tom Wigley for discussions and input to the calculations of radiative forcing from stratospheric ozone, Dr. Gunnar Myhre for discussions on parameterisation of radiative forcing from the various gases, Dr Fortunat Joos for historical CO₂ emission data and Dr. Guus Velders for halocarbon data. We also thank Odd Godal and Bård Romstad for help with the manuscript and postprocessing of the results as well as the annexes containing emissions numbers and historical concentrations.

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1 Background

Anthropogenic emissions affect climate by altering the concentration of several natural and man-made gases in the atmosphere. These gases interact with the radiative fluxes in the atmosphere thereby affecting the radiative balance and causing radiative forcing and climate change. Due to the many complex mechanisms and interactions in the climate system, very complex and sophisticated models are required for studying anthropogenic forcing of climate. General Circulation Models (GCMs) are used for such tasks. Due to heavy CPU demand, these models are not suited for scenario studies where a large number of model runs have to be done. They are also too large and resource demanding for incorporation in other models for integrated assessment studies that also focus on ecological, agricultural, economic and social effects of climate change.

Simple climate models (SCMs) are useful tools in analyses of man-made interactions with the climate system, and studies of different policies to limit the anthropogenic effects (e.g. Schlesinger and Jiang, 1991; Wigley and Raper, 1992; IPCC, 1995, 1996; Wigley, 1998), as well as in calculations and evaluation of the contribution from different gases to radiative forcing and climate change (e.g. Wigley, 1995; Smith and Wigley, 1998). Such models may also be useful in interdisciplinary research on policies to mitigate climate changes and adaptation strategies (e.g. Hammitt et al., 1996; Lempert et al., 1996; Yohe and Schlesinger, 1998).

This paper gives a documentation of a simple model for studying the relations between emissions, atmospheric concentrations, radiative forcing and change in global mean temperature and sea level. The changes in global temperature and sea level are calculated by an energy-balance-climate/up-welling diffusion ocean (EBC/UDO) model developed by Professor Micheal Schlesinger (see e.g. Schlesinger et al., 1992).

2 Overview of the model

Figure 1 shows the overall structure of the model, while figure 2 shows how the various program modules are related.

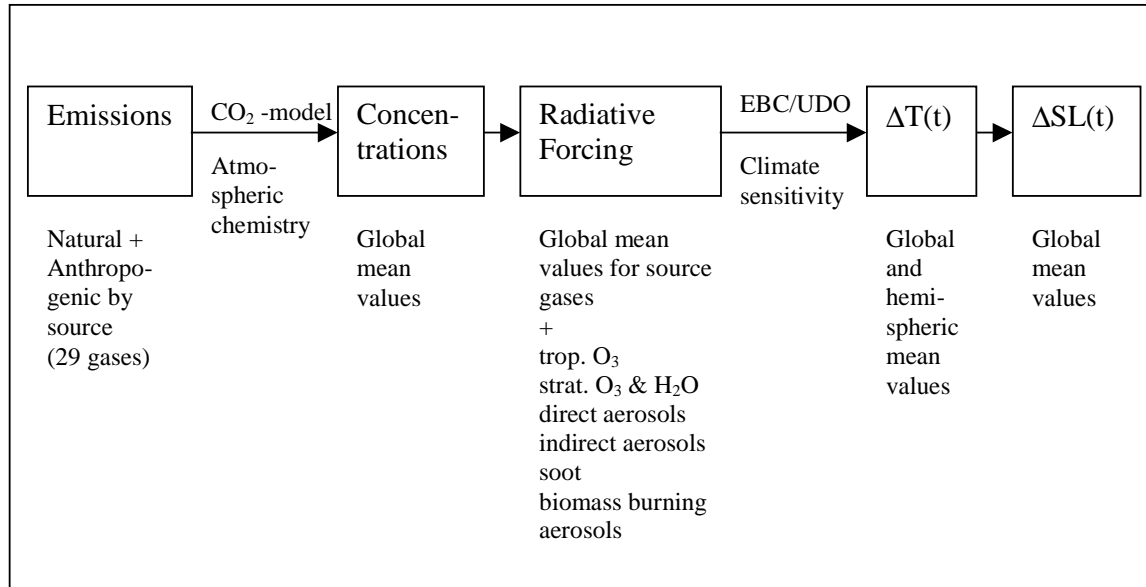
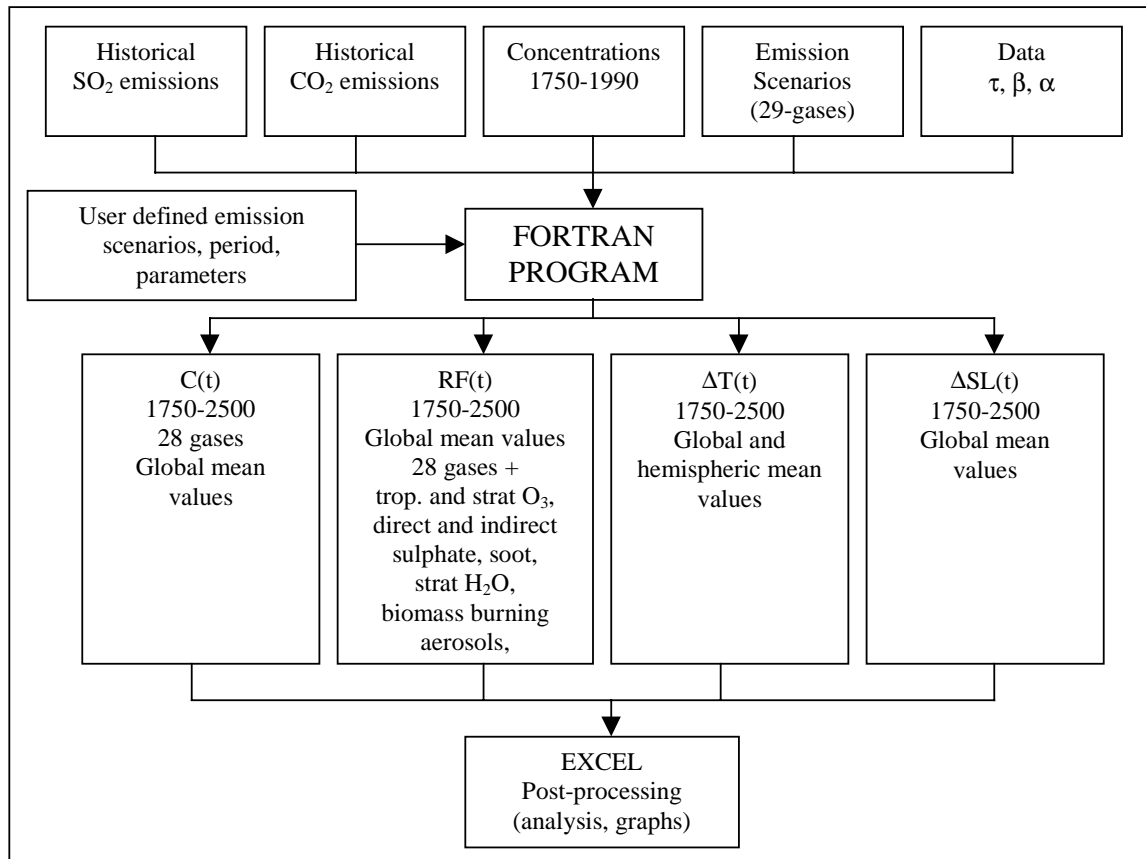


Figure 1: The conceptual structure of the model.

The 29 gases emitted (source gases) in the model are given in table 1. The *atmospheric concentrations* are calculated for all these gases except SO₂. *Radiative forcing* is calculated for the same gases and for tropospheric O₃, stratospheric O₃ and H₂O, sulphate and soot aerosols, aerosols from biomass burning and indirect forcing from aerosols.

For the period 1750 to 1990 historical concentrations are applied based on various sources (see section 5 and 6). For CO₂ the concentrations are calculated from 1750 up to the present and then further in to the future (see Joos et al., 1996; Alfsen and Berntsen, 1999). For the period beyond 1990 various scenarios can be applied.



τ : Atmospheric lifetime, β : conversion factor, α : radiative parameters

Figure 2: The file structure of the model.

In the “parameter file” the user can choose the period for the simulation, emission scenario, changes in the emissions of individual components relative to the chosen scenario and the names of the output files. Furthermore, climate sensitivity and magnitude of sulphate and ozone forcing in 1990 are also chosen.

The model is at this stage mainly based on the relations given in the IPCC reports (IPCC 1996 and IPCC, 1997). This version will then be used as a starting point for improvements based on new results in the literature and on our own studies with more complex and detailed models (e.g. Berntsen and Isaksen, 1997; Berntsen et al., 1997; Fuglestvedt et al., 1999).

The calculated forcing from 35 atmospheric components based on emission scenarios forms input to the energy-balance-climate/upwelling-diffusion-ocean (EBC/UDO) model developed by Schlesinger (see Figure 3). With prescribed values for climate sensitivity,¹ the model calculates changes in global and hemispheric mean temperatures as well as sea level rise due to thermal expansion of the ocean and melting of glaciers. The calculations are based on formulations for the exchange of energy between the atmosphere and the water surface and further down to the deep layers. The surface layer is set to a thickness of 75 meters, whereas the underlying part is split into 40 layers, each of thickness 100 meters. The transportation of cold water directly to the deep oceans in the arctic regions is accounted for. For further details of this model, see Schlesinger et al. (1992). The EBC/UDO model has a similar structure as the model used by IPCC in the Second Assessment Report (SAR) (IPCC, 1996) as described in IPCC (1997).

¹ Climate sensitivity usually refers to the long-term (equilibrium) change in global mean surface temperature following a doubling of atmospheric CO₂ (or equivalent CO₂) concentration ranging from 1.5 to 4.5°C. More generally, it refers to the equilibrium change in surface air temperature following a unit change in radiative forcing (°C/Wm⁻²), (IPCC, 1996).

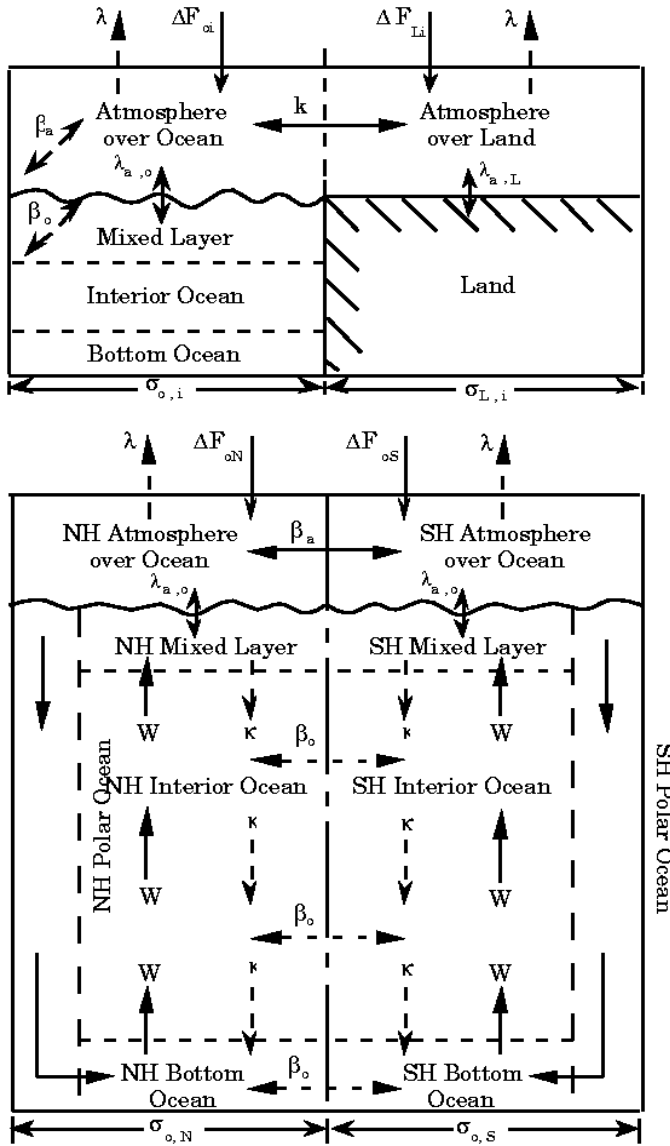


Figure 3: Schematic diagram of the simple climate/ocean model. The top panel shows the general structure of the model, and the bottom panel shows a vertical cross-section through the oceanic part. The symbols by the arrows indicate the following physical processes; ΔF_{Li} and ΔF_{oi} : tropopause radiative forcing in hemisphere i over land and ocean, respectively; λ : radiative-plus-feedback temperature response of the climate system; k : atmospheric land-ocean heat exchange; β_a atmospheric interhemispheric heat exchange; $\lambda_{a,o}$: air-sea heat exchange; $\lambda_{a,L}$: air-land heat exchange; β_o : oceanic interhemispheric heat exchange; W : vertical heat transport by upwelling; κ :vertical heat transport by diffusion. The quantities $\sigma_{o,i}$ and $\sigma_{L,i}$ denote the fractions of hemisphere i covered by land and ocean, respectively. Schlesinger et al., 1992.

Table 1: Source gases included in the model.

CO ₂	Carbon dioxide
CH ₄	Methane
N ₂ O	Nitrous oxide
SO ₂	Sulphur dioxide
CCl ₃ F	CFC-11
CCl ₂ F ₂	CFC-12
CCl ₂ FCClF ₂	CFC-113
CClF ₂ CClF ₂	CFC-114
CF ₃ CClF ₂	CFC-115
CHClF ₂	HCFC-22
CF ₃ CHCl ₂	HCFC-123
CF ₃ CHClF	HCFC-124
CH ₃ CFCl ₂	HCFC-141b
CH ₃ CF ₂ Cl	HCFC-142b
C ₃ HF ₅ Cl ₂	HCFC-225ca
C ₃ HF ₅ Cl ₂	HCFC-225cb
CCl ₄	Carbon tetrachloride
CH ₃ CCl ₃	Methylchloroform
C ₂ HF ₅	HFC-125
CH ₂ FCF ₃	HFC-134a
CH ₃ CHF ₂	HFC-152a
CHF ₃	HFC-23
CBrClF ₂	H-1211
CBrF ₃	H-1301
CBrF ₂ CBrF ₂	H-2402
CH ₃ Br	Methylbromide
CF ₄	Perfluoromethane
C ₂ F ₆	Perfluoroethane
SF ₆	Sulphur hexafluoride

3 Emissions

A description of the procedure for generating the emission files is found in the annexes. The IPCC IS92-scenarios are used for the gases included in these scenarios (IPCC 1992). For the gases regulated by the Montreal Protocol and its amendments, the additional information given in table 2.5 in SAR WG1 is used.

For gases not included in the IPCC scenarios or regulated by the Montreal Protocol and its amendments, assumptions about future emissions have been made (see chapter 8).

4 Calculations of concentrations from emissions

4.1 Carbon dioxide (CO₂)

A program module based on the parameterisation given by Joos et al. (1996) is described in Alfsen and Berntsen (1999). The parameterisation is developed from studies with complex carbon cycle models and applies an ocean mixed-layer pulse response function that characterises the surface to deep ocean mixing in combination with a separate equation describing air-sea exchange. The use of a mixed-layer pulse response function avoids the problem arising from the non-linearities of the carbon chemistry and gives therefore more accurate results. The overturning of assimilated carbon in the terrestrial biosphere is described by a decay response function, while an equation for the net primary productivity is also included. A time step of 0.5 month is used. Concentrations of CO₂ are calculated from 1750 based on data for fossil fuel emissions and deforestation (Joos, pers. comm., 1997).

4.2 Methane (CH₄)

The atmospheric concentration of methane is determined by the mass balance equation:

$$dC/dt = P - Q \cdot C = E/\beta - C \cdot (1/\tau_{\text{atm}} + 1/\tau_{\text{soil}})$$

C is the mixing ratio of methane (ppbv), P the production rate, β is a factor for conversion of emissions to mixing ratio (TgCH₄/ppbv), τ is the lifetime (in years) and Q is the loss rate. Values for τ and β are given in table 2.

Assuming that the production (E/β) and loss (Q) terms are constant during the time step, the differential equation above is solved to give:

$$C_t = E/\beta \cdot Q + (C_{t-1} - E/\beta \cdot Q) \cdot e^{-Q \cdot \Delta t}$$

where the loss term is $Q = 1/\tau_{\text{total}} = (1/\tau_{\text{atm}} + 1/\tau_{\text{soil}})$. This equation describes the development of the atmospheric concentration of methane. The time step Δt used for all gases (except CO₂) is one year.

The main sink of methane is reaction with OH in the atmosphere. IPCC gives a lifetime of 9.08 years. In addition uptake in soil contributes to the loss of methane from the atmosphere. This lifetime is 150 years. The total loss rate (year⁻¹) for atmospheric methane is then $(1/9.08 + 1/150) = 1/8.56$.

Several studies of atmospheric chemistry have shown that methane influences its own lifetime since the reaction between CH₄ and OH also is a significant loss reaction for OH (Isaksen and

Hov, 1987; Isaksen et al., 1992; Berntsen et al., 1992; Lelieveld and Crutzen, 1992; Fuglestvedt et al., 1996; IPCC, 1995). Increased emissions and higher atmospheric levels of CH₄ thus decrease the levels of OH. This will increase the chemical lifetime of CH₄, thereby further increasing the atmospheric levels of CH₄. For a 10% increase in emission and a reference concentration at the present level, the relative increase in concentration is estimated to be 37% larger than the relative increase in the emission of methane (Fuglestvedt et al., 1996). When the emissions of CH₄ are doubled this is estimated to ca 50%. For comparison, Hauglustaine et al. (1994) calculate a feedback strength of 40% for a doubling of the CH₄ emissions.

To properly calculate the future levels of methane this effect is so large that it should be taken into account. Osborn and Wigley (1994) parameterised this effect in a manner suited for SCMs. Based on results given in Isaksen et al. (1992), Berntsen et al. (1992) and Fuglestvedt et al. (1996), they derived the following relation:

$$\tau_{\text{atm}} = \tau_{\text{atm}}^0 \cdot (C/C_0)^N$$

where $N = 0.238$

According to the documentation of the MAGICC model (Wigley, 1994), N is adjusted based on newer information. If the exponent in the expression given above is set equal to 0.3 a much better agreement with the concentrations given in IPCC is found than if the factor is set to 0.238.

As in IPCC 1995, the IS92a emissions were adjusted so that the calculated concentrations in the 1990s match the observed concentrations. The emissions for the IS92a scenario (511 Tg CH₄/yr in 1990) of methane were increased by 69 Tg CH₄/yr, which is well within the uncertainty range given in the emission inventory for this gas. This is done for all years and is a redefinition of the baseline emission of methane. Good agreement is found between our calculated methane mixing ratios and those given by IPCC (1995) in table 2.5.

4.3 Nitrous oxide (N₂O)

The mass balance equation

$$dC/dt = P - Q \cdot C = E/\beta - C \cdot (1/\tau)$$

is used to model the development in N₂O. The lifetime (τ) is kept fixed at 120 years, see table 2.

As in IPCC 1995, the IS92a emissions were adjusted so that the calculated concentrations in the 1990s match the observed concentrations. The emissions for the IS92a scenario of N₂O were increased by 3.4 TgN/yr for all years, which is within the uncertainty range given in the emission inventory. This is done for all years and is a redefinition of the baseline emission of this gas. Very good agreement is found between our calculated mixing ratios and those given by IPCC (1995) in table 2.5 for the period 1990-2100.

4.4 CFCs, HCFCs, HFCs and other halocarbons

The same mass balance equation as for N₂O is used for CFCs, HCFCs, HFCs and other halocarbons. The values for τ and β (with references) are given in table 2. Very good agreement is found between our calculated future concentrations and the values in table 2.5 in IPCC (1995).

5 Calculations of radiative forcing

A change in average net radiation at the tropopause, due to a change in the fluxes of either long-wave or short-wave radiation, has been defined as a *radiative forcing of climate*. A radiative forcing disturbs the balance between incoming and outgoing radiation at the tropopause, but over time a new balance is established as climate responds to the radiative forcing. A *positive radiative forcing* has a *warming* effect and a *negative* has a *cooling* effect. Radiative forcing gives a first order estimate of the climate change potential of the mechanism under consideration (IPCC, 1995).

In this SCM we use highly parameterised expressions of the radiative forcing of each substance following IPCC (1996; 1997). The parameterisations are based on detailed calculations in radiative transfer models (see IPCC, 1990; 1996; 1997 and references therein).

5.1 Carbon dioxide (CO₂)

For the radiative forcing from changes in CO₂, IPCC (1997) gives the following formula:

$$RF = \alpha \ln(C(t)/C_0) / \ln 2$$

Where $\alpha = 4.37$ and C is the mixing ratio of CO₂ in ppmv.

In IPCC 1990 this formula is written as

$$RF = 6.3 \ln(C(t)/C_0)$$

which is equal to the first formula since $4.37/\ln 2 = 6.3$

The former formulation is preferred in IPCC (1997) for transparency since the coefficient 4.37 is equal to the forcing that is assumed (based on more detailed studies) for a doubling of the CO₂ levels. According to IPCC (1997) the forcing of 4.37 W/m² is about 0.5 W/m² too high. Myhre et al. (1998) give $\alpha = 3.7$ W/m² (when stratospheric temperature adjustment is taken into account).

In the present version of the model, the formula given in IPCC (1997) is used. In the WMO Ozone Assessment (WMO, 1999) a new and different relation is given for the CO₂ forcing. However, Myhre et al. (1998) find that with their parameter ($\alpha = 3.7$), the formulation given above gives a very good parameterisation of the CO₂ forcing.

5.2 Methane (CH₄)

IPCC (1997) gives the following formula for radiative forcing from changes in methane:

$$RF = \alpha \cdot [(C(t)^{0.5} - (C_0)^{0.5}) - (f(C, N_0) - f(C_0, N_0))]$$

The second term on the right hand side of the equation is a correction term for overlap with N₂O, given by:

$$f(C, N) = 0.47 \ln [1 + 2.01 \cdot 10^{-5} (C \cdot N)^{0.75} + 5.31 \cdot 10^{-15} C \cdot (C \cdot N)^{1.52}]$$

Where C is the mixing ratio of methane (ppbv) and N is the mixing ratio of N₂O (ppbv) and C₀ and N₀ are the concentrations for 1750.

IPCC (1997) gives 0.036 for α , while Myhre et al. give 0.039.

5.3 Nitrous oxide (N₂O)

IPCC (1997) gives the following formula for radiative forcing from changes in N₂O:

$$RF = \alpha \cdot [(N(t)^{0.5} - (N_0)^{0.5}) - (f(C_0, N) - f(C_0, N_0))]$$

The second term on the right side of the equation is a correction term for overlap with methane, given above.

IPCC (1997) gives $\alpha = 0.14$, while Myhre et al. give 0.125.

5.4 CFCs, HCFCs, HFCs and other halocarbons

For the CFCs, HCFCs, HFCs and the other halocarbons included in this model, radiative forcing is proportional to the change in mixing ratio:

$$RF = \alpha \cdot (C(t) - C_0)$$

Values for α (in Wm⁻²/pptv) with references are given in table 2. In the present version of the model we use the values for α and τ given by IPCC (1995) and IPCC (1997).

Table 2: Values applied for tau, beta and alpha.

GAS	TAU (τ) (years)	Ref.	BETA** (β)	Ref.	ALFA (α)	Ref.
CO ₂			2.123	(1)		
CH ₄ ***	8.56	(1)	2.78	(1)		
τ atmosphere	9.08	(1)				
τ soil	150	(1)				
N ₂ O	120	(1)	4.8	(1)		
CFC-11	50	(1)	22.6	(1)	2.20E-04	(1)
CFC-12	102	(1)	20.8	(1)	2.80E-04	(1)
CFC-113	85	(1)	32.5	(1)	2.80E-04	(1)
CFC-114	300	(1)	29.7	(1)	3.20E-04	(1)
CFC-115	1700	(1)	27.1	(1)	2.60E-04	(1)
CCl ₄	42	(1)	25.3	(1)	1.00E-04	(1)
CH ₃ CCl ₃	4.9	(1)	22.0	(1)	5.00E-05	(1)
HCFC-22	12.1	(1)	14.9	(1)	1.90E-04	(1)
HCFC-141b	9.4	(1)	26.3	(1)	1.40E-04	(1)
HCFC-123	1.4	(1)	20.1	(1)	1.80E-04	(1)
HCFC-124	6.1	(1)	22.9	(2)	1.90E-04	(1)
HCFC-142b	18.4	(1)	16.9	(2)	1.80E-04	(1)
HCFC-225ca	4.2	(1*)	35.9	(3)	2.60E-04	(1)
HCFC-225cb	4.2	(1*)	35.9	(3)	2.60E-04	(1)
HFC-134a	14.6	(1)	17.5	(1)	1.70E-04	(1)
HFC-125	32.6	(1)	20.6	(1)	2.00E-04	(1)
HFC-152a	1.5	(1)	10.5	(1)	1.10E-04	(1)
HFC-23	264	(1)	11.6	(3)	1.80E-04	(1)
H-1211	20	(1)	28.4	(4)	3.00E-04	(6)
H-1301	65	(1)	25.6	(4)	3.20E-04	(1)
H-2402	20	(1)	46.0	(3)	-	(7)
CH ₃ Br	1.2	(1)	16.4	(5)	-	(7)
CF ₄	50000	(1)	15.1	(2)	1.00E-04	(1)
C ₂ F ₆	10000	(1)	23.7	(2)	2.30E-04	(1)
SF ₆	3200	(1)	25.8	(3)	6.40E-04	(1)

References:

- 1: IPCC, 1996.
 - 2: Wigley and Reeves, 1991: Global Warming Potentials, A report to the UK dep. of the Environment and the Hadley Centre for Climate Prediction and Research.
 - 3: Estimated according to formula given by Wigley and Reeves, 1991.
 - 4: Wigley 1998 (priv. communication).
 - 5: Estimated from data in WMO 1994.
 - 6: WMO, 1999
 - 7: Alpha is assumed equal to zero.
- * Average of the lifetime of HCFC-225ca and HCFC-225cb
 ** Units for beta: CO₂: Pg(C)/ppmv. CH₄ and N₂O: Tg/ppbv. Halocarbons: Gg/pptv.
 *** $1/\tau_{\text{tot}} = 1/\tau_{\text{atm}} + 1/\tau_{\text{soil}}$. Values from IPCC Technical Paper II, 1997.

5.5 Tropospheric ozone

In the calculations of future ozone concentrations carried out in IPCC (1996) and IPCC (1997) only ozone increases from increased methane levels are taken into account. The following equation is given in IPCC (1997)²:

$$RF = 8.62 \cdot 10^{-5} \cdot \Delta CH_4$$

The ozone forcing for 1990 from emissions of NO_x, CO and VOC is set to 0.32 W/m², and kept constant after this time. The ozone forcing from methane increases is set to 0.08 W/m² based on a forcing sensitivity of 0.02 Wm⁻²/ppbv O₃ and the assumption that ozone has increased by 4 ppbv since pre-industrial times due to methane. Together this forcing adds up to 0.4 W/m², which is in the middle of the range from several studies referred to in IPCC 1995. Newer studies give somewhat lower estimates (e.g. Berntsen et al., 1997) which will be taken into account in later versions of the model. Changes in ozone from changes in NO_x, CO, VOC and other factors are not taken into account in calculations of future forcing from tropospheric ozone.

The hemispheric weights for the global forcing are 1.29 (NH) and 0.74 (SH), based on Berntsen et al. (1997).

5.6 Stratospheric ozone

Several model studies calculate negative radiative forcing from loss of stratospheric ozone. These calculations are very sensitive to the vertical distribution of the ozone loss, and some studies find positive forcing from the observed or modelled loss of stratospheric ozone since the late seventies (Myhre et al., 1998; Hauglustaine et al., 1994). See Myhre (1998) for an overview of the different estimates of radiative forcing from stratospheric ozone depletion.

In IPCC (1996), based on the work of Wigley (i.a. Wigley and Raper, 1992; Wigley, 1994), the stratospheric O₃ loss is assumed to vary with tropospheric chlorine concentration to the power 1.7, plus a bromine loading term which is weighted relative to chlorine by a factor of 40 at present. The forcing from stratospheric O₃ loss is then assumed to be directly proportional to the ozone loss. This leads to the formula given in IPCC (1997):

$$RF = -[0.000552 \cdot \Sigma(\{NCl_i C_i\}^{1.7}) + 3.048 \cdot \Sigma(NBr_i C_i)] / 1\ 000$$

² Based on several model studies, IPCC (1995) concluded that ozone increases by 1.5 ppbv for 20% increase in methane. Applied together with the forcing sensitivity given above, the following relation is found:
 $RF_{O_3} = 0.02 \text{ Wm}^{-2}/\text{ppbv } O_3 \cdot \Delta O_3 = 0.02 \text{ Wm}^{-2}/\text{ppbv } O_3 \cdot (1.5 \text{ ppbv } O_3 / 1715 \cdot 0.2 \cdot CH_4) \cdot \Delta CH_4 = 8.8 \cdot 10^{-5} \cdot \Delta CH_4$
 which is similar to the formula given above from IPCC (1997). Note typographical error in the formula for this forcing in Appendix 2 in IPCC (1997). The forcing shall be calculated from change in *concentration* of CH₄, not radiative forcing from CH₄.

C_i is the tropospheric concentration (in pptv) of chlorine- or bromine-containing gas i , NCl_i and NBr_i are the numbers of chlorine or bromine atoms in gas i , and the summation is over all gases considered. In the model, the contribution (600 pptv) from natural CH_3Cl is taken into account (tab. 2.5d,ii in IPCC 1995). The relation was calibrated by comparing the calculated global mean forcing due to stratospheric ozone changes with detailed radiative transfer calculations based on observed changes in ozone between 1979 and 1990 (IPCC, 1997). For the total direct halocarbon forcing in 1990, IPCC calculates 0.27 W/m^2 . This is offset by -0.17 W/m^2 from stratospheric ozone depletion giving a net forcing of 0.1 W/m^2 . Comparison with the results from complex models shows very good agreement (IPCC, 1997). The Br-gases H-1211 and H-1301 are included in the calculations of radiative forcing from stratospheric O_3 . A time lag of 3 years between the tropospheric and stratospheric chlorine and bromine concentrations is applied (in accordance with Solomon and Daniel, 1995 and WMO, 1994). We have not included explicit calculations of the stratospheric concentrations of ozone³.

In the formulation for the ozone forcing given above, the chlorine concentrations from the individual gases are raised to the power 1.7 separately, and then all the weighted contributions are summarised. On physical/chemical grounds it would be expected that the *total chlorine loading* should be raised to a given power based on a recalibration instead of the individual contributions. The formula given by IPCC is based on the assumption that each gas has its own contribution to stratospheric ozone forcing, and that these contributions are linearly additive. Under this assumption, the formula given in IPCC (1997) is correct (Wigley, pers. comm.) A new formulation that weights the total chlorine could be an alternative to the one given above.

5.7 Stratospheric water vapour

Early studies indicated that the production of water vapour in the stratosphere represents a large indirect effect of methane emissions. In IPCC (1990) this effect was given as 30% of the direct effect. In WMO (1992) it was given as 22-38%. Lelieveld and Crutzen (1992) found 5%, while Hauglustaine et al. (1994) calculated 1-2%. Calculations by Wang, given in Fuglestvedt et al. (1996), yield 5%. The radiative forcing associated with increased levels of H_2O due to methane build-up is given by IPCC (1997) as:

$$RF = 0.05 \cdot RF_{CH_4\text{-pure}}$$

$RF_{CH_4\text{-pure}}$ means that the methane forcing must be given without taking into account the overlapping with N_2O . This relation is used for the period 1750 to 1990 and in calculations of future forcing.

³ In IPCC 1995 calculation of delta O_3 (%) is based on the observed relation between observed chlorine loading and percentage change in ozone. In 1979 the chlorine level was 2.44 ppbv Clx while in 1990 it was 3.64 ppbv Clx. Delta ozone (global mean) between 1979 and 1990 was -2%. Delta ozone per delta Clx is then $dO_3/dClx = -2\%/1.2 \text{ ppbv Clx} = -1.67\%/ppbv \text{ Clx}$.

5.8 Direct forcing from sulphate aerosols

The future forcing from scattering of solar radiation by sulphate aerosols (the direct effect) is given by IPCC (1997) as:

$$RF = (e(t) / e_{1990}) \cdot RF_{dir, 1990}$$

In IPCC (1997) e_{1990} is 69 TgS/yr. In the IS92a scenario the 1990 emission is 76 TgS/yr, so in order to start at the 1990 value for radiative forcing, e_{1990} is set to 76 TgS. This includes only anthropogenic emissions.

The radiative forcing for 1990 ($RF_{dir, 1990}$) is set equal to -0.3 W/m^2 . The best estimate for the direct forcing from *sulphate*, based on detailed calculations, is -0.4 W/m^2 . In the expression for future forcing given above, -0.3 W/m^2 is used to take into account the positive forcing from absorption of terrestrial long wave radiation by atmospheric soot, estimated to $+0.1 \text{ W/m}^2$.

The hemispheric weights for the global forcing are 1.6 (NH) and 0.4 (SH), based on Schlesinger et al. (1992)

5.9 Indirect forcing from sulphate aerosols

The radiative forcing from changes in distribution and properties of clouds caused by increased levels of aerosols is in IPCC (1997) given as:

$$\Delta Q = \frac{\log(1 + e(t) / e_{nat})}{\log(1 + e_{1990} / e_{nat})} \cdot \Delta Q_{1990}^{indirect}$$

where $\Delta Q_{1990}^{indirect} = -0.8 \text{ W/m}^2$, and $e_{nat} = 42 \text{ TgS/yr}$ and $e_{1990} = 76 \text{ TgS/yr}$.

5.10 Biomass burning aerosols

Based on estimates given in IPCC 1995 the radiative forcing from biomass burning aerosols is -0.2 W/m^2 in 1990, and kept constant thereafter.

6 Historical data

For the period 1750 to 1990 we use for all non-CO₂ gases observed or estimated concentrations from the literature as shown in the annexes.

The forcing from tropospheric O₃ driven by the changes in NO_x and VOC (0.32 W/m², see above) is scaled by the emissions of CO₂ from fossil fuels. The other component of the forcing from tropospheric ozone (0.08 W/m²) follows the methane development. The forcing from stratospheric water vapour also follows the development of the methane concentration (see section 5.7).

The historical development of forcing from soot is scaled by the CO₂ emissions from the use of fossil fuels. For sulphate (direct and indirect) we use the emission history given by Schlesinger et al. (1992).

The time development of the biomass burning aerosol forcing is in the present version based on net deforestation, while gross forestation is preferable (IPCC, 1996).

7 Uncertainties

The results from a model as the one described in this report is subject to significant uncertainties, some of which are very difficult to estimate the magnitude of. There are uncertainties related to each of the modules shown in figure 1.

- Future emission scenarios are related to factors such as population growth, technological and economical development, and even possible feedback from climate change. With simple climate models like this one, the range of possible outcome from a great number of scenarios can be studied due to the limited computer resources need for each model simulation.
- Limitations in our understanding of the sources, sinks and possible chemical transformation of many of the major GHGs add to the uncertainties when atmospheric concentrations of a given set of emissions are calculated in the model. In comparison with the uncertainties in the other processes in the model, this is probably not a major factor. One major exception is how SO₂ emissions transforms to sulphate particles, which again interact with cloud formation.
- From the estimated concentrations of GHGs, the radiative forcing is calculated by a set of highly parameterised equations. For the well mixed (i.e. longlived) GHGs this can be checked against detailed calculations, and the agreement is generally good. For the shorter lived gases, which are chemically more active (i.e. ozone and sulphate particles), the parameterisations are not so good because the forcing depends on the regional distribution of the species which is calculated by the model. Figure 4 from IPCC (1996) gives an overview of the magnitudes of the different contributions to radiative forcing. This figure also gives important information about the level of confidence for the different estimates. For the well-mixed GHGs the uncertainties are reasonable, but for all the substances that have shorter lifetimes and thus are less well mixed in the atmosphere, the uncertainties are larger. For ozone and sulphate, the confidence for the estimates are described as low, while for aerosols from biomass burning and soot, and especially the indirect forcing from cloud changes, the confidence is very low. For the latter forcing, no central value is given in IPCC (1996) due to lack of knowledge. However, in IPCC (1997), a value of -0.8 W/m² is used in the formula for calculation of future forcing from this mechanism.
- When the radiative forcing is known the EB/UD module calculates how the climate responds in terms of global average temperature change. A major uncertainty here is the climate sensitivity (i.e. how large is the global annual average temperature change for a doubling of the CO₂ concentrations when the system is allowed to reach a new equilibrium). The uncertainty arises from our limited understanding of the feedback processes (changes in amount of water vapour, surface albedo, cloud cover and optical properties, etc.) in the climate system. In this model the climate sensitivity is fixed as described above, and due to the low computational costs of the model it is possible to run it with different values of this key parameter (cf. section 8.1.4 and figure 15). However the model focus on transient simulations where the climate system is not in equilibrium, mainly due to the slow transport of heat to the deep ocean. In the model (cf. figure 3) the transport of heat to the deep ocean is parameterised through diffusion coefficients and a parameter Π , describing the downwelling

at high latitudes. These parameters are based on simulations with 3-D global ocean models, but they are still poorly understood, and they are not allowed to change over time.

- To perform more detailed impact studies, an understanding of how the local or at least the regional climate is changing is required. In the next step of the project this will be carried out based on results from global coupled atmosphere/ocean climate models (GCMs). This adds an additional uncertainty to the results as even if the GCMs agrees fairly well on the global level there are large differences in the regional change, in particular in parameters linked to the hydrological cycle (precipitation, soil moisture, etc.).

Even though there are significant uncertainties in the results, and many of the processes that contributes are not represented explicitly in the model, there is need for this kind of models in climate research when used in an educated way and in interaction with GCMs (cf. Mitchell et al., 1999). Due to the low computational costs, it is possible to perform Monte Carlo type simulations to investigate the total uncertainty in a way that is not possible or desirable with GCMs.

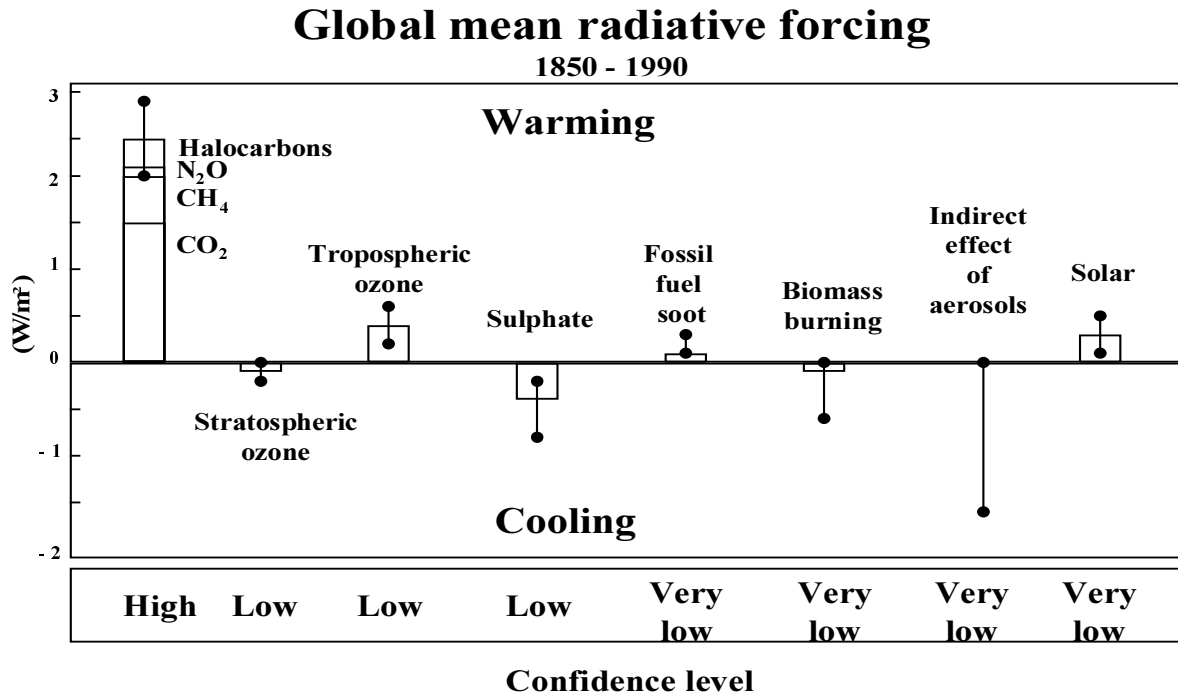


Figure 4: Estimates of the globally and annually averaged anthropogenic radiative forcing (W/m^2) due to changes in concentrations of climate gases and aerosols from pre-industrial times to the present (IPCC, 1996). The level of uncertainty in the estimates is indicated by the uncertainty bars, and the confidence levels for the estimates are given below.

8 Some results

Below some examples of results from the SCM is given. In these model runs we have used the IPCC relations and values to the extent that is possible, and in some cases used values from other sources (see table 2). The emission scenario IS92a, IS92c and IS92e, together with additional assumption about other species, are applied.

The emissions of CF_4 and C_2F_6 are kept at the present levels, while the emissions of SF_6 follows scenario 1 in Ko et al. (1993). Emissions of H-1211 and H-1301 are taken from Wigleys SCM MAGICC (Wigley pers. com.). New emission numbers for the ozone depleting substances (ODS) are given in WMO Ozone assessment (WMO, 1999), and these will be included in a later version. Table 3 shows the assumptions that have been made about future emissions of source gases included in the model.

Table 3: References for future emissions.

CO ₂	IS92a, c and e
CH ₄	I IS92a, c and e
N ₂ O	IS92a, c and e
SO ₂	IS92a, c and e
CFC-11	IPCC 1995, table 2.5d,ii
CFC-12	IPCC 1995, table 2.5d,ii
CFC-113	IPCC 1995, table 2.5d,ii
CFC-114	IPCC 1995, table 2.5d,ii
CFC-115	IPCC 1995, table 2.5d,ii
HCFC-22	IPCC 1995, table 2.5d,ii
HCFC-123	IPCC 1995, table 2.5d,ii
HCFC-124	IPCC 1992, table A3.11
HCFC-141b	IPCC 1995, table 2.5d,ii
HCFC-142b	IPCC 1992, table A3.11
HCFC-225ca	IPCC 1992, table A3.11*
HCFC-25cb	IPCC 1992, table A3.11*
CCl ₄	IPCC 1995, table 2.5d,ii
CH ₃ CCl ₃	IPCC 1995, table 2.5d,ii
HFC-125	IPCC 1992, table A3.11
HFC-134a	IPCC 1992, table A3.11
HFC-152a	IPCC 1992, table A3.11
HFC-23	Based on Oram et al. (1998)**
H-1211	Wigley (pers. com.)
H-1301	Wigley (pers. com.)
CF ₄	Constant at present level.
C ₂ F ₆	Constant at present level.
SF ₆	Ko et al. (1993)

* In IPCC 1992 only the emissions of HCFC-225 is given. We have distributed the emissions equally between HCFC-225ca and cb.

** HFC-23 is a by-product of HCFC-22. The future emissions of HFC-23 are scaled to the emissions of HCFC-22.

8.1 Results from model runs based on the IS92 scenarios

Some results from model runs based on the IPCC IS92 emission scenarios are given below.

8.1.1 Future concentrations

Figure 5 shows the modelled future concentrations of CO₂ for the emissions scenarios IS92a, IS92e and IS92c. By the end of the next century the CO₂ concentration has reached 724 ppmv in

the IS92a scenario, while a level of 488 is reached in the low emission scenario IS92c. The high emission scenario IS92e passes the concentration level of 800 ppmv in year 2085. The corresponding developments of the methane and nitrous oxide levels are shown in figure 6 and 7, respectively. It should be noted that on a time scale like this and with the large changes in the high emissions scenarios, there are large uncertainties connected to modelling future concentrations.

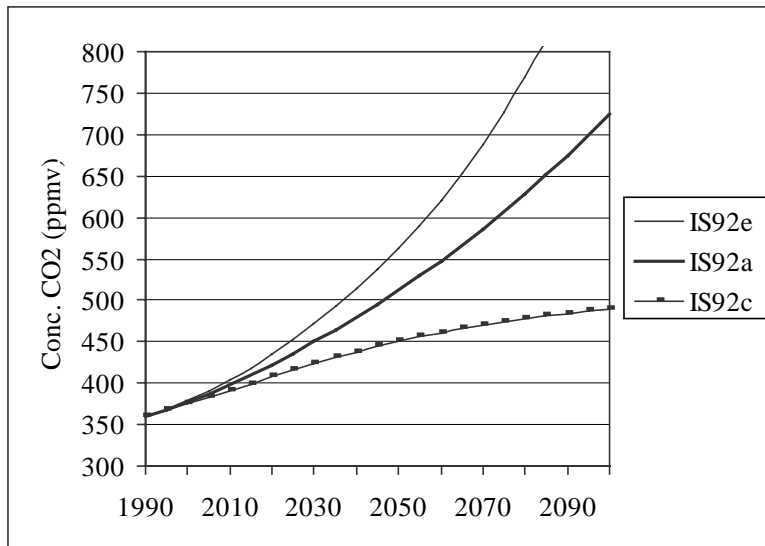


Figure 5: Modelled CO₂ concentrations in the IS92e, IS92a and IS92c scenarios.

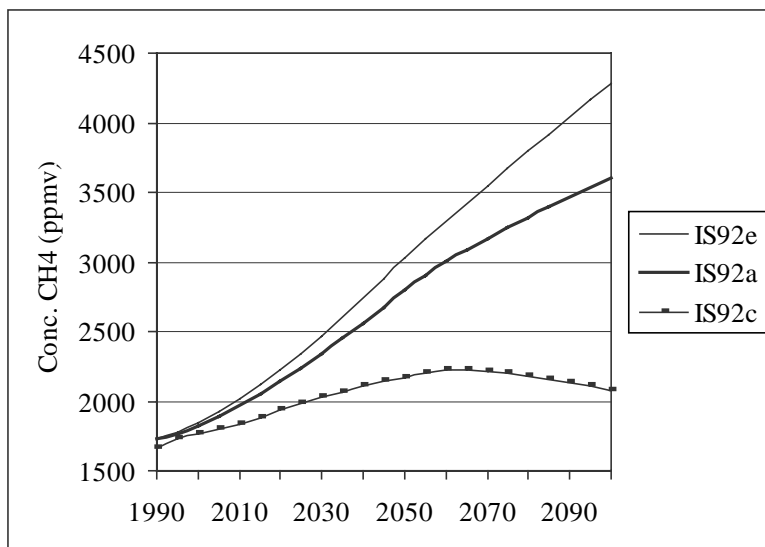


Figure 6: Modelled CH₄ concentrations in the IS92e, IS92a and IS92c scenarios.

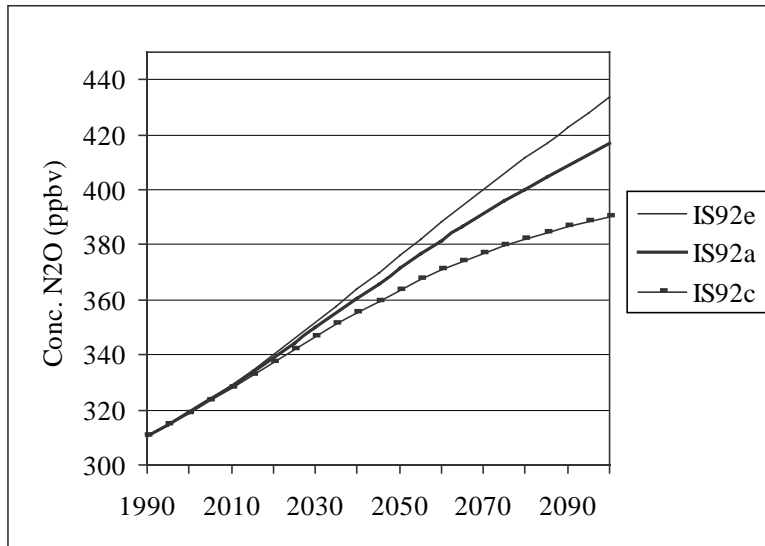


Figure 7: Modelled N₂O concentrations in the IS92e, IS92a and IS92c scenarios.

Figures 8 and 9 show the development of the concentrations of some of the halocarbons included in the model. The emissions of these gases are consistent with the Montreal Protocol and its amendments (London 1990 and Copenhagen 1992). The ozone depleting gases CFC, CCl₄, CH₃CCl₃ and HCFC-22 are phased out while increased emissions are assumed for the HFCs shown here based on information given in IPCC (1996).

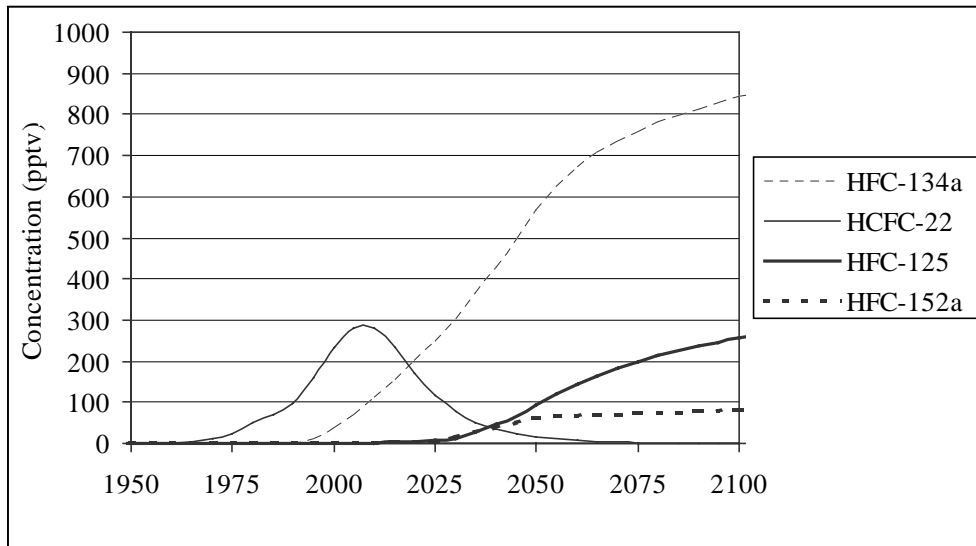


Figure 8: Modelled concentrations of some halocarbons in the IS92a scenario.

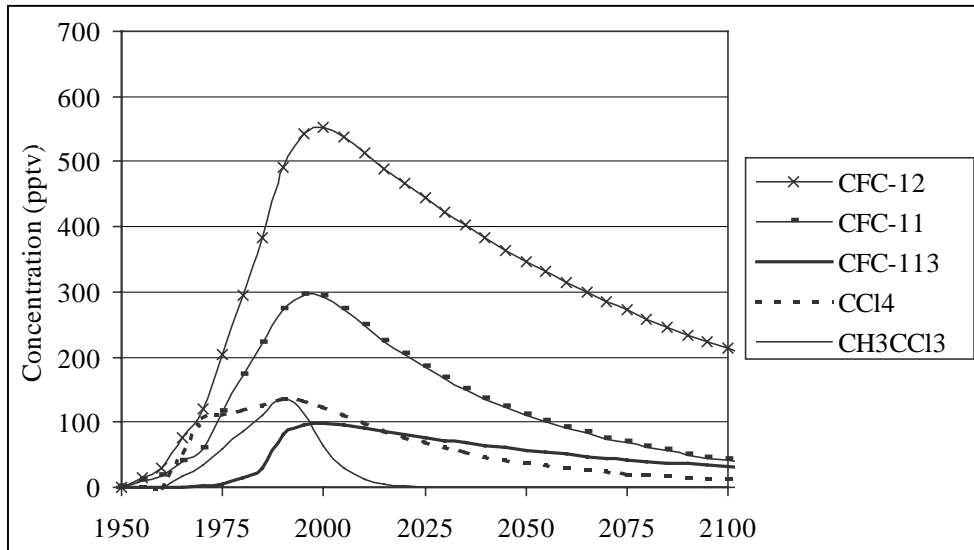


Figure 9: Modelled concentrations of some halocarbons in a Copenhagen-like scenario applied for all IS92-scenarios.

8.1.2 Future radiative forcing

Based on the calculated future concentrations of the gases, the changes in the radiative balance (*i.e. radiative forcing*) are calculated. Figure 10 shows the future radiative forcing for the non- CO_2 gases when the IS92a scenario is used. The negative forcing from stratospheric ozone reduction is seen to reach maximum in year 2000. After this time the negative forcing approaches zero as the ozone layer recovers. The time profile for direct effect of the ozone depleting gases has a similar shape, but with opposite sign.

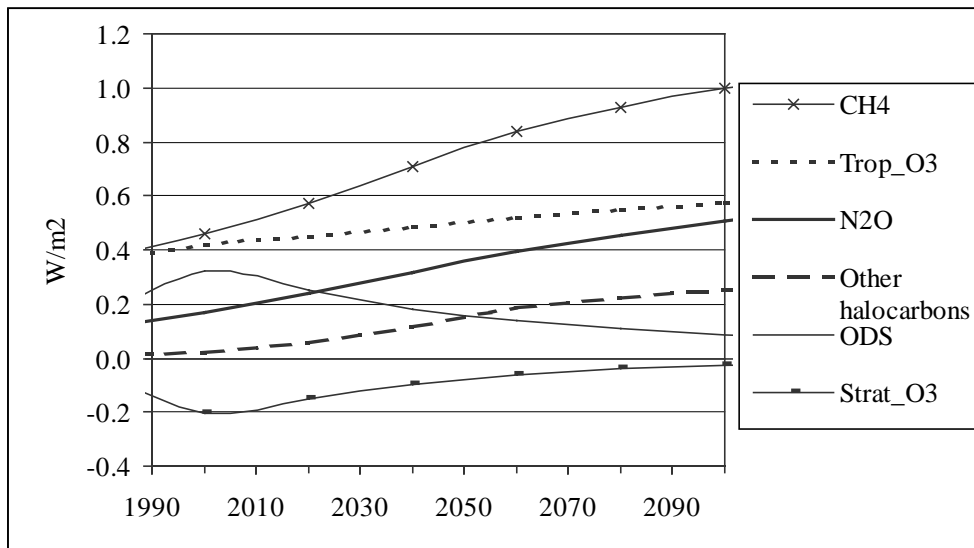


Figure 10: Modelled future radiative forcing in the IS92a scenario.

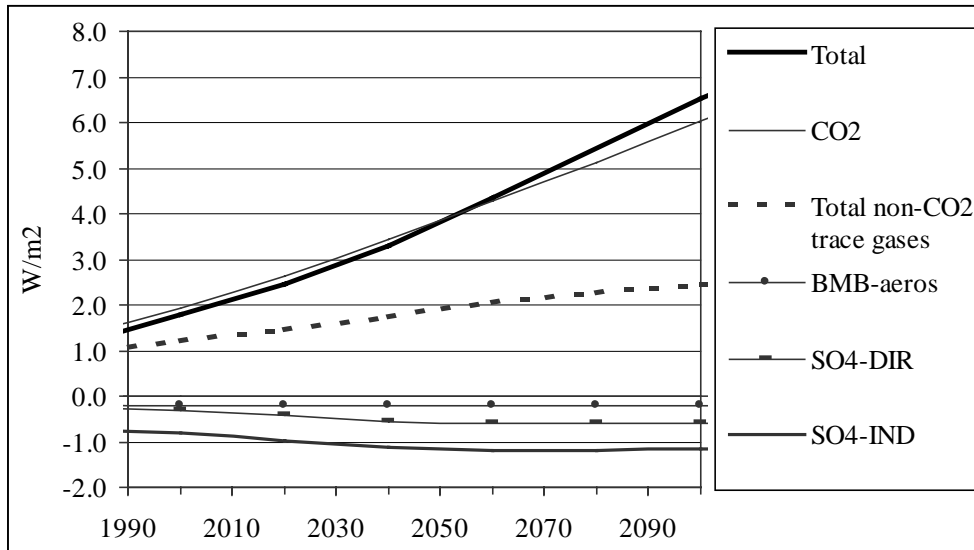


Figure 11. Modelled future radiative forcing in the IS92a scenario.

Figure 11 gives the total forcing together with the contributions from CO₂, total non-CO₂ gases and aerosols based on the IS92a scenario. The negative forcings from the aerosols increase slightly throughout the century, while the forcing from non-CO₂ gases levels off.

The total forcing for the three scenarios IS92a, IS92c and IS92e are shown in figure 12. The range of these scenarios is from 4 to 8 W/m² by the end of the next century.

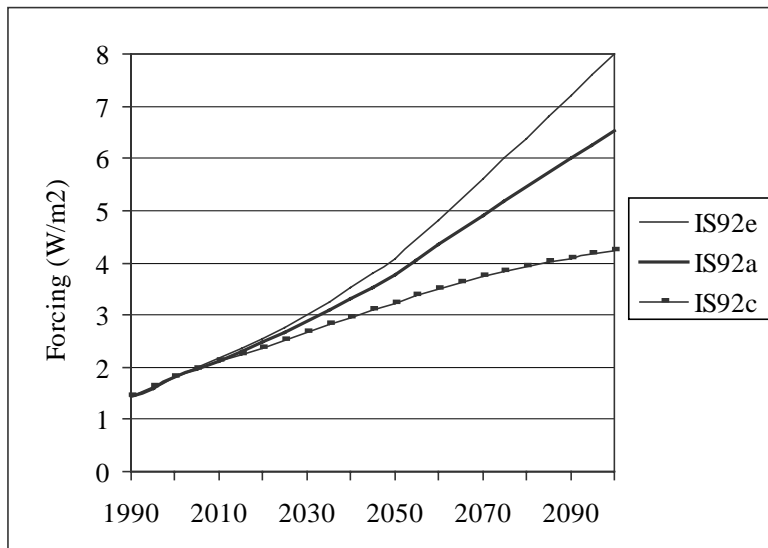


Figure 12. Modelled total forcing in the IS92e, IS92a and IS92c scenarios.

8.1.3 Future changes in temperature and sea level

The calculated changes in global mean temperature relative to 1990 for the three scenarios are shown in figure 13. The IS92a scenario gives a warming of 2.3°C in 2100, while IS92e and IS92c give 2.8 and 1.4°C, respectively. The corresponding changes in sea level from the melting of glaciers and thermal expansion of the ocean are shown in figure 14. The IS92a scenario gives a sea level rise of 0.4 m relative to 1990, while IS92e and IS92c give 0.5 and 0.3 m, respectively.

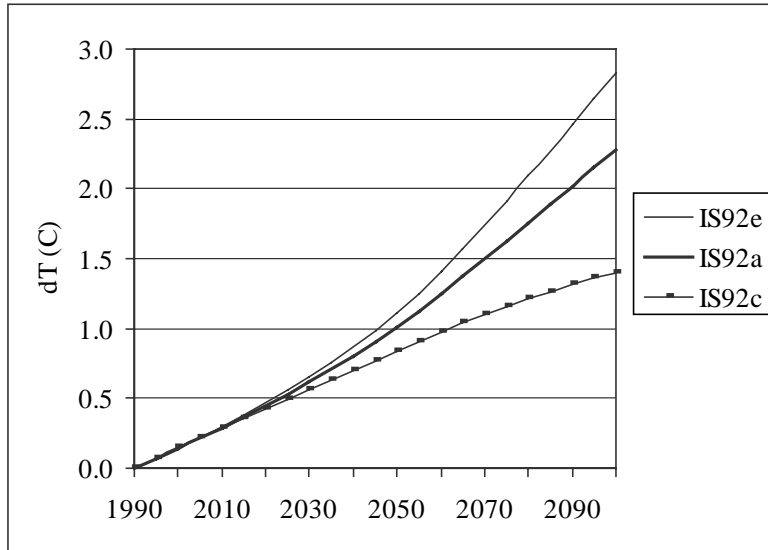


Figure 13: Modelled temperature change relative to 1990 levels in the IS92e, IS92a and IS92c scenarios.

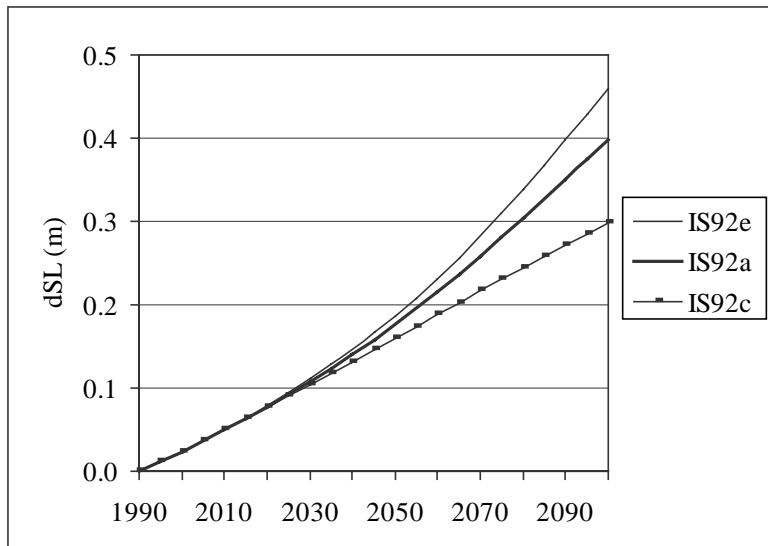


Figure 14: Modelled sea level rise relative to 1990 for the IS92e, IS92a and IS92c scenarios.

8.1.4 Various climate sensitivities

The future emission of climate gases is one of the main uncertainties in predictions of future man-made climate change. In addition, the sensitivity of the climate system to radiative forcing is uncertain. This sensitivity reflects the strengths of the feedback processes in the climate system (see chapter 2 and 7). The change in global mean surface air temperature at equilibrium for a doubling of the CO₂ level is usually used as a benchmark. Based on the current knowledge, a doubling of CO₂ concentration, is calculated to give a warming of 1.5–4.5°C at equilibrium, with a best estimate of 2.5°C. Climate sensitivity can not be estimated by a SCM, but is prescribed based on studies with GCMs and paleo climate studies (see e.g. Hoffert and Covey, 1992). How clouds respond to global warming is a critical uncertainty in the understanding of the climate system and is a major reason for the large range.

Figure 15 shows the future warming based on IS92a for the prescribed sensitivities 1.5, 2.5 and 4.5°C. A low sensitivity (1.5) results in a warming of 1.5 °C in 2100 relative to 1990, while high sensitivity (4.5) gives a warming of 3.5°C. Compared to the range of global warming in 2100 from the three emission scenarios (fig. 13), the temperature range from the sensitivity range is larger.

Figure 16 shows the spread in sea level change from these three estimates of future warming. It should be noted that this is not illustrating the effects of uncertainties in ice melt parameters and thermal expansion of the ocean as only the effect of different climate sensitivities are taken into account.

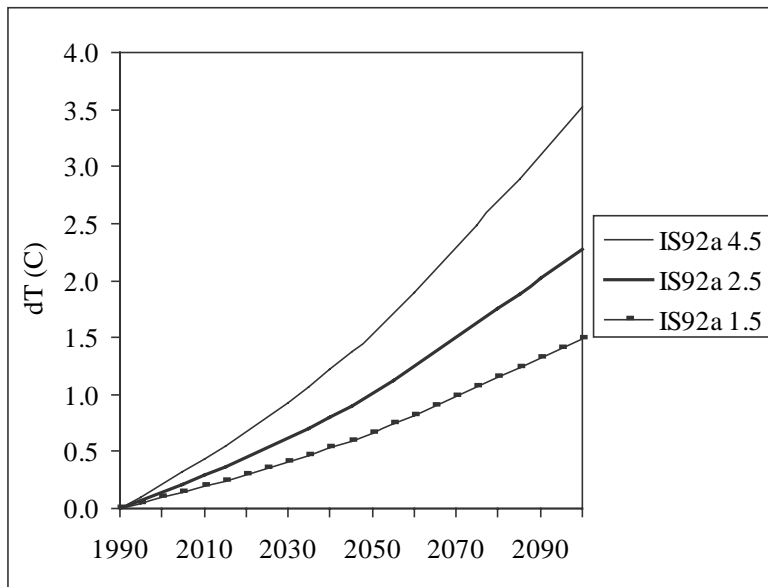


Figure 15: Modelled temperature changes relative to 1990 levels using various climate sensitivities on the IS92a scenario.

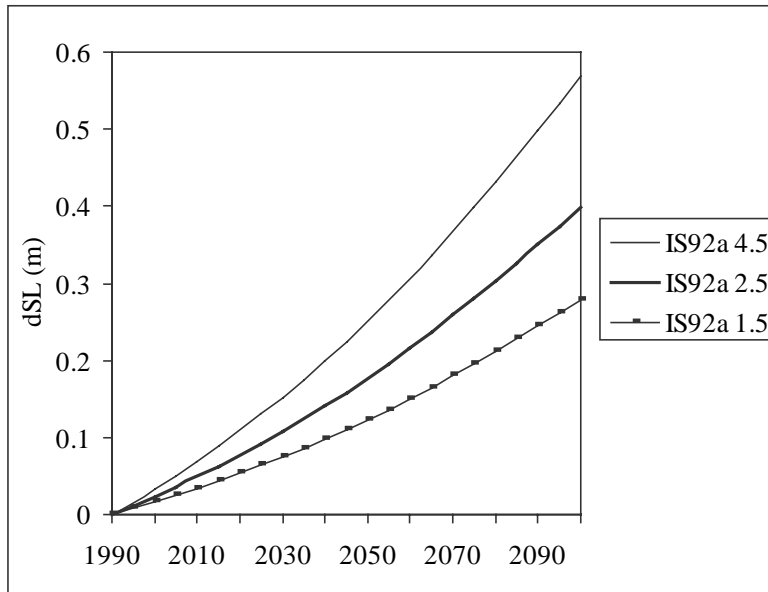


Figure 16: Modelled change in sea level rise relative to 1990 levels using various climate sensitivities for the IS92a scenario.

8.1.5 Changes on longer timescales

The IS92 emission scenarios give emissions up to the year 2100 and the changes in temperature and sea level are usually studied on this time scale. But due to the large inertia in the climate system, the emission up to 2100 will cause changes in concentrations, temperature and sea level for centuries after this time. Even if the emissions of CO₂ and other climate gases were reduced strongly after 2100, global mean temperature and sea level would continue to rise for some time.

Figure 17 shows the calculated forcing from a model test in which all man made emissions are reduced linearly to zero over the period 2100 to 2200 and kept at zero to 2500. The negative aerosol forcings approach zero without any lag due to the short lifetime of sulphate, while the CO₂ forcing and the total forcing continue to rise for some decades. The total forcing peaks around 2160 when a decline in forcing starts, mainly governed by CO₂. The calculated temperature change is shown in figure 18. Delayed relative to the forcing shown in figure 17, the global mean temperature continues to increase to year 2190 and then starts to decline very slowly. The corresponding change in sea level is shown in figure 19. Even if the man made emissions are reduced to zero in 2200 and the temperature starts to decline, a slow rise in global mean sea level continues for several centuries.

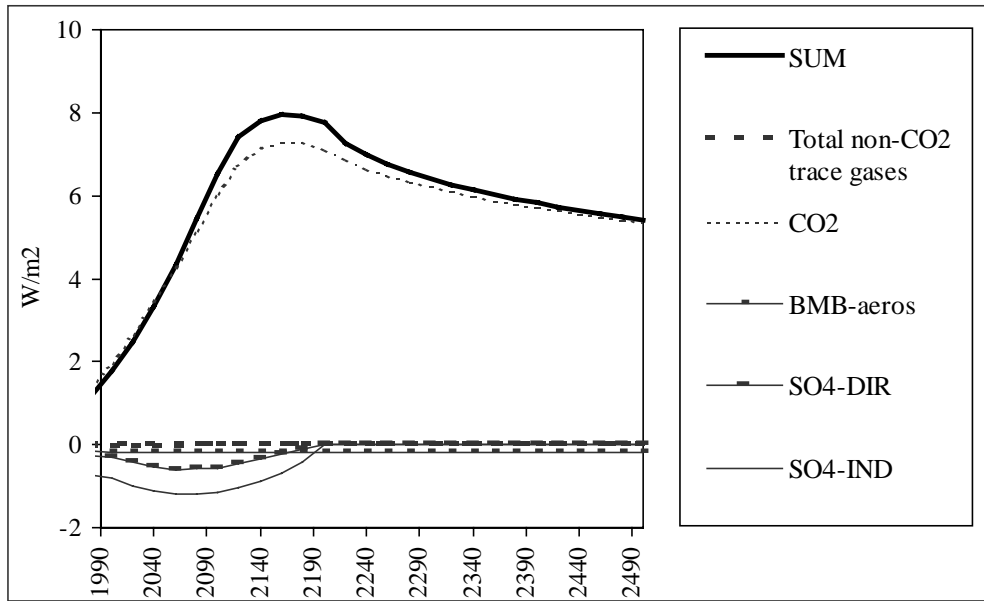


Figure 17: Modelled radiative forcing when emissions are reduced from the IS92a scenario in 2100 to zero in 2200 and kept at zero to 2500.

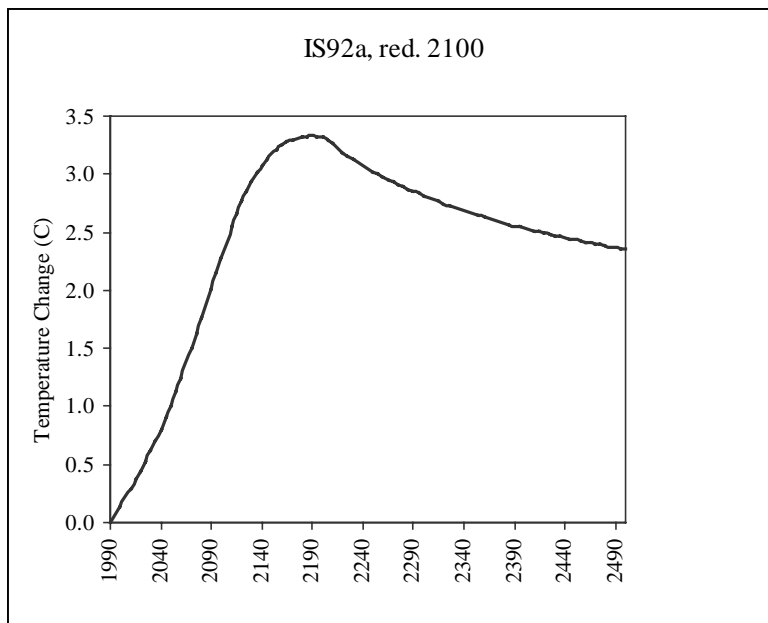


Figure 18: Modelled temperature rise compared to 1990 levels when emissions are reduced from the IS92a scenario in 2100 to zero in 2200 and kept at zero to 2500.

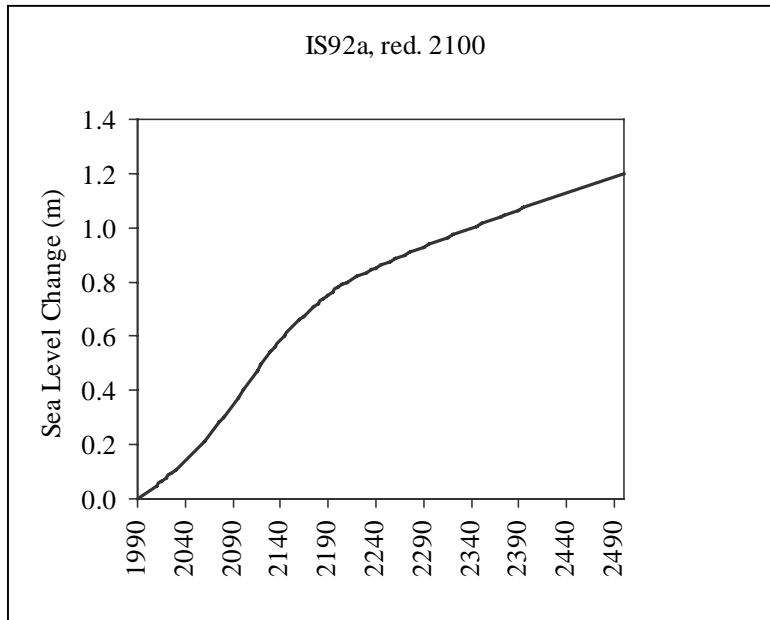


Figure 19: Modelled change in sea level rise compared to 1990 levels when emissions are reduced from the IS92a scenario in 2100 to zero in 2200 and kept at zero to 2500.

These results for global mean temperature and sea level rise are in agreement with other studies with both complex and simple climate models (Manabe and Stouffer, 1993, 1994; Raper et al., 1996, IPCC 1995, pp 324 and 388). The residual sea level rise is due to the large heat capacity of the ocean and the slow warming of the deeper layers which give continued thermal expansion of the oceans. The simple ice sheets models included in the calculations give continuing effects on ice volumes after the temperature has levelled off due to the assumed large response times involving ice dynamics.

8.1.6 Comparison with other results

In this section we will present a comparison of the output from our simple climate model with results published by the IPCC (1996). In general we find very good match when comparing the computed future concentration and radiative forcing in our model with the IPCC results. This is expected since we use similar relations and expressions as IPCC for concentration and forcing from emission change. However, due to differences in modelling the change in temperature, caused by the change in forcing, our model produces in general slightly higher temperature estimates compared to the results presented by the IPCC. Our temperature estimates for the IS92a, IS92c and IS92e scenarios in year 2100 are approximately 0.1-0.3°C higher compared to the IPCC results. When altering the climate sensitivity when the IS92a scenario is applied, our estimates are in the order of 0.1-0.5°C higher. The sea level rise estimates in the year 2100 are on the contrary about 0.1m lower than the one published by the IPCC for all emission scenarios.

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Annexes: Compilation of greenhouse gas data

By Bård Romstad and Jan S. Fuglestad

Annex I: Historical concentrations

Data for historical GHG concentrations are taken from the IPCC publications (IPCC 1990 and 1995), various published articles, WMO (1992), chapter 11 in WMO (1999) and the MAGICC model (Wigley and Raper, 1997). Table 4 gives a complete list of the references for historical concentrations.

Table 4. References for historical concentrations of GHGs.

GHG	Reference
CO ₂	Wigley and Raper (1997)
CH ₄	Wigley and Raper (1997)
N ₂ O	IPCC 1990 (table 2.5.b)
CFC-11	IPCC 1995 (table 2.5.d)
CFC-12	IPCC 1995 (table 2.5.d)
CFC-113	IPCC 1995 (table 2.5.d)
CFC-114	IPCC 1995 (table 2.5.d)
CFC-115	IPCC 1995 (table 2.5.d)
CCl ₄	IPCC 1995 (table 2.5.d)
CH ₃ CCl ₃	IPCC, 1996 (table 2.5.d)
HCFC-22	IPCC, 1996 (table 2.5.d)
HCFC-141b	IPCC, 1996 (table 2.5.d)
HCFC-123	IPCC, 1996 (table 2.5.d)
HCFC-142b	IPCC, 1996 (figure 2.11)
CF ₄	Harnisch et al. (1996)
C ₂ F ₆	Harnisch et al. (1996)
SF ₆	IPCC, 1996 (figure 2.12)
H-1211	WMO 1992 (table 8-3)
H-1301	WMO 1992 (table 8-3)
H-2402	WMO 1999
CH ₃ Br	WMO 1999
HFC-23	Oram et al. (1998)

Formatting the data

Data from IPCC (1996), table 2.5.d

For these gases (see Table 4) values are given for every 5th year from 1970. Gases with non-zero values in 1970 have been extrapolated by assuming that concentrations were zero in 1960 and a linear increase the first ten years. An exception is made for CFC-11 and CFC-12 where 1960 values are taken from IPCC 1990 and zero concentrations are anticipated in 1950 (as depicted for CFC-11 in figure 3, page xvi, IPCC 1990).

Data read from figures in IPCC (1996)

In lack of other references, concentrations for HCFC-142b and SF₆ are reproduced from figure 2.11 and 2.12 respectively in IPCC (1996). These figures starts in 1978, therefore concentrations for previous years are extrapolated linearly between the concentrations in 1980 and assumed zero concentrations in 1970.

Data from the MAGICC model

In the MAGICC model (Wigley and Raper, 1997) historical concentrations for CO₂ and CH₄ are given for every 5th year from 1765. We have used the data just as they are, and made an extrapolation by regression for the first 15 years. In IPCC (1995) the pre-industrial concentration of CH₄ is suggested to be ~700 ppbv, but figure 9 in the same publication shows that the MAGICC value of 790 ppbv in 1765 is within the range of the ice-core measurements.

N₂O

Atmospheric concentration of N₂O are given in IPCC 1990, table 2.5, for the years 1765, 1900, 1960, 1970, 1980 and 1990. In IPCC (1995) though, the pre-industrial concentration is anticipated to be approximately 275 ppbv. We have used this as our 1750 value, overruled the IPCC 1990 values for 1765 and 1900, and made a linear interpolation between the 1750 value from IPCC (1995) until the 1960 value from IPCC 1990.

Data from WMO 1992

For H-1211 and H-1301 values are given in WMO (1992) table 8-3. There are values for 1970, 1975, 1980, 1985 and 1990. We have used these values directly and assumed zero concentrations before 1970.

CF₄ and C₂F₆

Concentrations for CF₄ and C₂F₆ are reproduced from figure 4 in Harnisch (1996). This figure starts at 1980 so we continued the linear trend until it reached natural background levels, 44 pptv and 0 pptv, respectively (Harnisch, 1996).

H-2402 and CH₃Br

Values for H-2402 and CH₃Br are taken from WMO (1999). Concentrations are given for every year between 1900 and 2100, so our values are a selection of every fifth of the values between 1900 and 1990.

HFC-23

Values are reproduced from figure 1 in Oram et al. (1998), which shows concentrations measured at Cape Grim over the period 1978-1995. Like the data from IPCC (1996) extrapolation have been made by assuming linear growth from zero-concentrations in 1960 until the 1980 value of 3.4 pptv.

Historical CO₂ emissions

Values for historic CO₂ emissions are taken from Bruno and Joos (1997). The emissions for fossil fuel burning are zero from 1750 to 1850 and emissions from land-use change are positive at all times. Values are presented on an annual basis, measured in giga tonnes (Gt) carbon per year.

Historical anthropogenic SO₂ emissions

Values for historic SO₂ emissions are taken from Schlesinger et al. (1992). The emissions are zero from 1750 to 1850. Values are presented on an annual basis, measured in Tg sulphur per year.

Presentation of formatted data

Below follows figures of historical concentrations for some of the gases mentioned above. For more gases and exact values see Annex III.

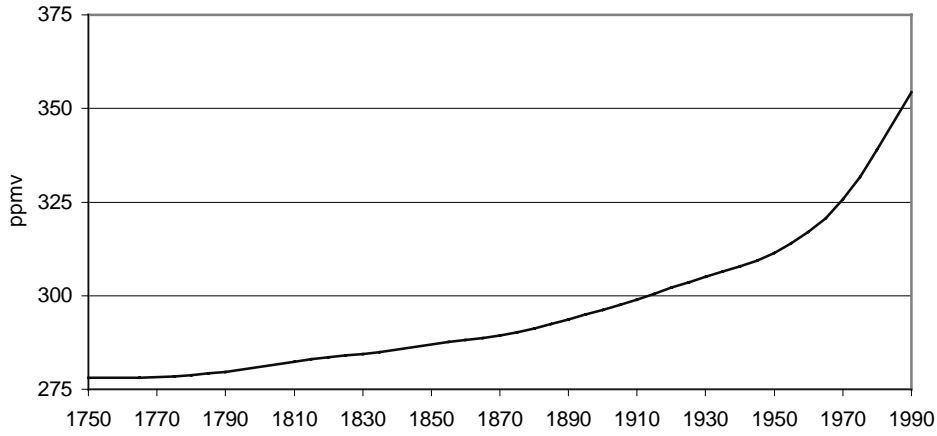


Figure 20: Concentration of CO₂ in the atmosphere, 1750-1990 (ppmv).

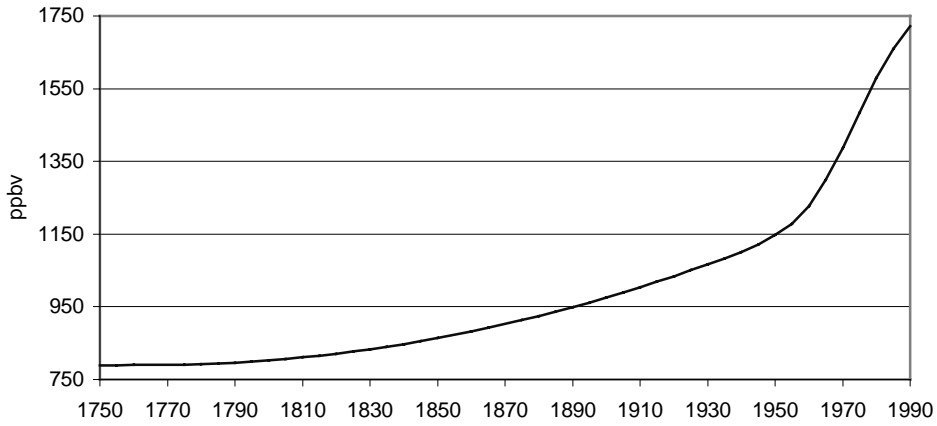


Figure 21: Concentrations of CH₄, 1750-1990 (ppbv).

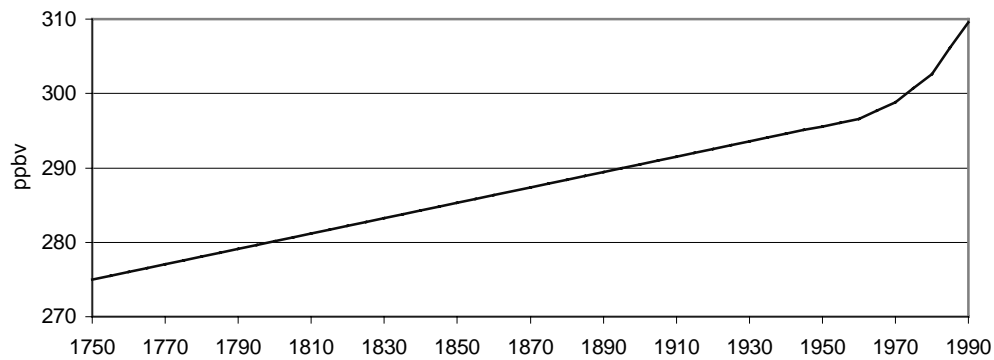


Figure 22: Concentrations of N₂O, 1750-1990 (ppbv).

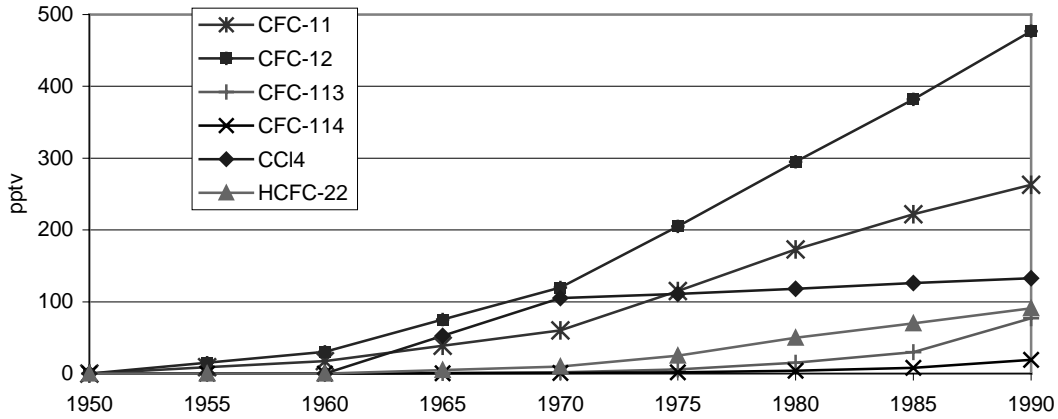


Figure 23: Concentrations of some halocarbons, 1950-1990 (pptv).

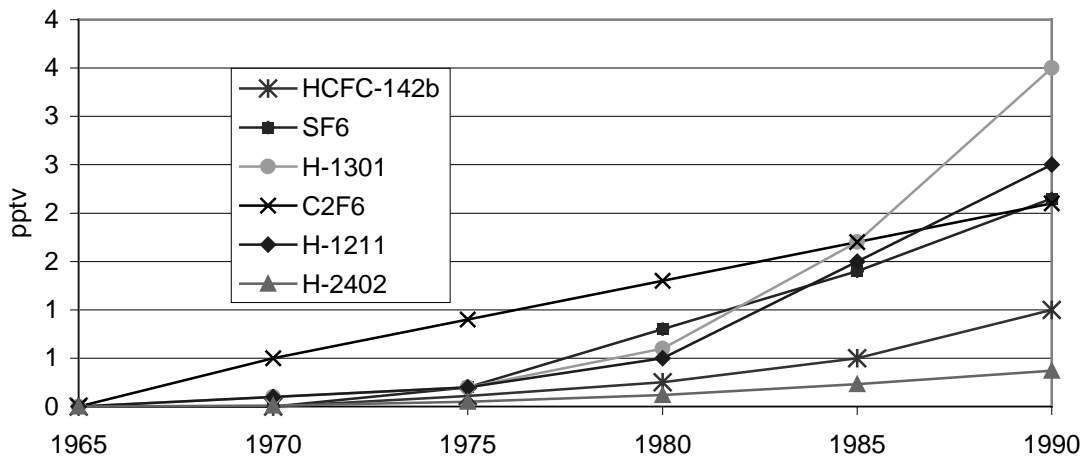


Figure 24: Concentrations of some halocarbons, 1965-1990 (pptv).

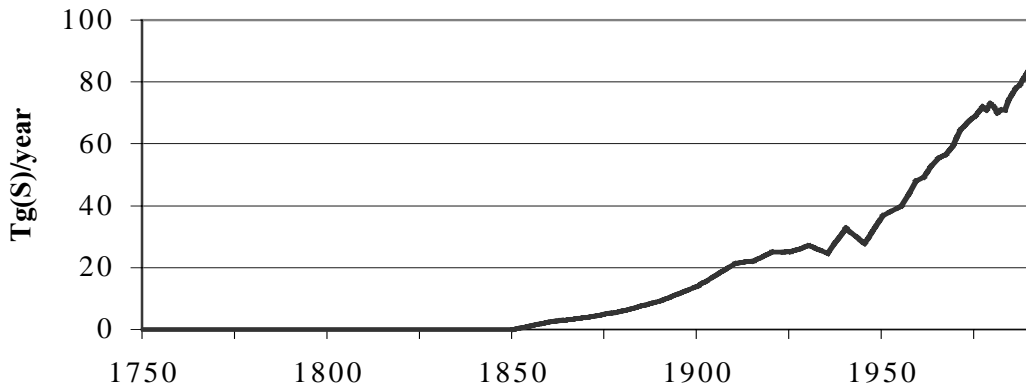


Figure 25: Historical emissions of sulphur. 1750-1990 (Tg S / year)

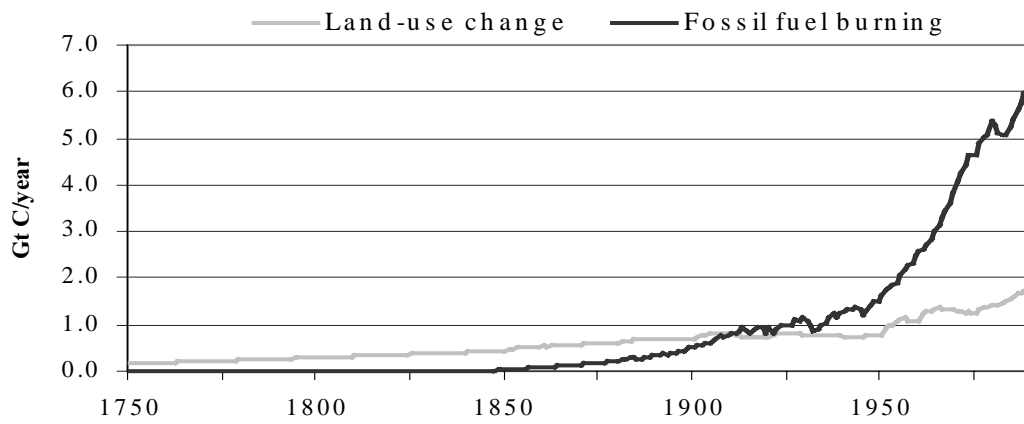


Figure 26: Historical emissions of carbon. 1750-1990 (Gt C / year)

Annex II: Future emissions

Data compilation

The future emissions presented in this paper are based on the IPCC IS92a scenario as this is the scenario mostly used and referred to until now. New scenarios are being developed by IPCC and the IS92 scenarios may soon be out of use. Most of the data are taken directly from the IPCC reports (1992, 1994 and 1995), but for some gases, not included in the IPCC scenarios, assumptions have been done based on other references (see Table 5).

Table 5. References for future GHG emission data.

GHG	Reference	Comments
CO ₂	Morita and Lee (1997)	IS92a
N ₂ O	Morita and Lee (1997)	
CH ₄	Morita and Lee (1997)	
SO ₂	Morita and Lee (1997)	
CFC-11	IPCC, 1996, table 2.5d ii	Copenhagen-like scenario adapted for chlorocarbons used with all IS92 scenarios
CFC-12	IPCC, 1996, table 2.5d ii	
CFC-113	IPCC, 1996, table 2.5d ii	
CFC-114	IPCC, 1996, table 2.5d ii	
CFC-115	IPCC, 1996, table 2.5d ii	
CCl ₄	IPCC, 1996, table 2.5d ii	
CH ₃ CCl ₃	IPCC, 1996, table 2.5d ii	
HCFC-22	IPCC, 1996, table 2.5d ii	
HCFC-141b	IPCC, 1996, table 2.5d ii	
HCFC-123	IPCC, 1996, table 2.5d ii	
HCFC-124	IPCC 1992, table A3.11	IS92a
HCFC-142b	IPCC 1992, table A3.11	
HCFC-225ca	IPCC 1992, table A3.11	
HCFC-225cb	IPCC 1992, table A3.11	
HFC-134a	IPCC 1992, table A3.11	
HFC-125	IPCC 1992, table A3.11	
HFC-152a	IPCC 1992, table A3.11	
CF ₄	Wigley and Raper (1997)	
C ₂ F ₆	Wigley and Raper (1997)	
SF ₆	Ko et al. (1993), table 4, scenario	
H-1211	Wigley pers. comm.	
H-1301	Wigley pers. comm.	
H-2402	WMO 1999	
CH ₃ Br	WMO 1999	
HFC-23	Oram et al. (1998)	

Formatting the data

For the gases included in IPCC (1996) table 2.5d ii, values are given as five year interval averages (1990-1994,1995-1999 etc.). To make these numbers fit into our format we had to transform the intervals into series of yearly values.

HFC-23 is a by-product of HCFC-22 production. The relationship between these two gases is described in Oram et al. (1998), and we calculated this relationship to be 0.0272:1. All other series are made directly by a linear interpolation between the values given in the references.

Presentation of formatted data

Below follows figures of emission scenarios for some of the gases mentioned above. For more gases and exact values, see Annex III.

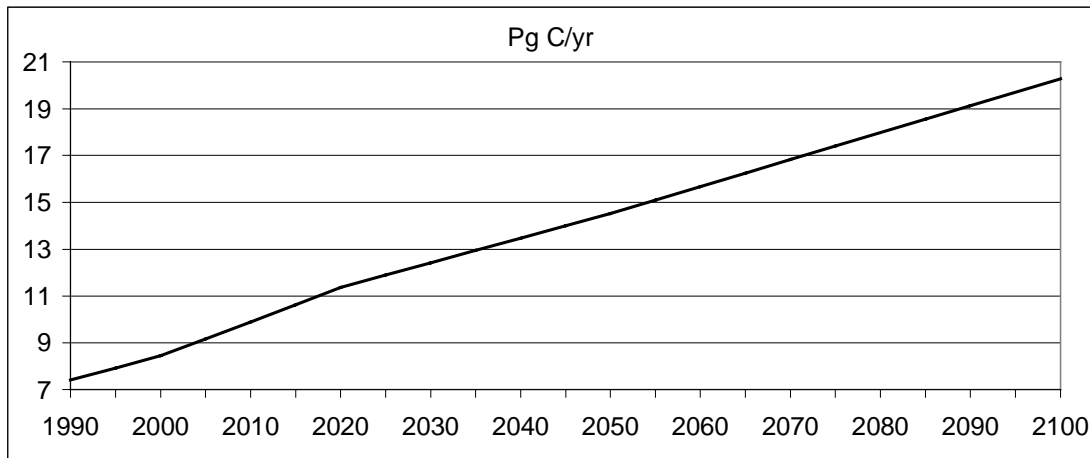


Figure 27: IS92a scenario for CO₂ 1990-2100 (Pg C/yr)

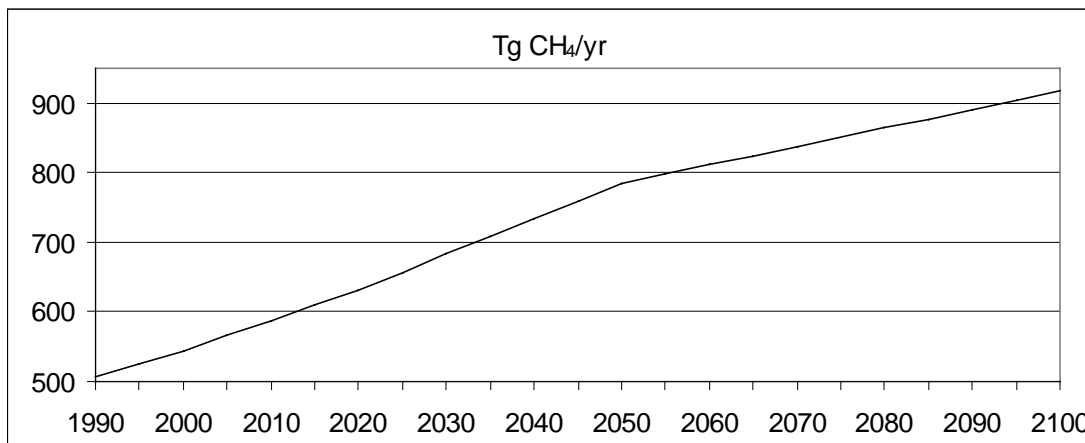


Figure 28: IS92a scenario for CH₄ 1990-2100 (Tg/yr)

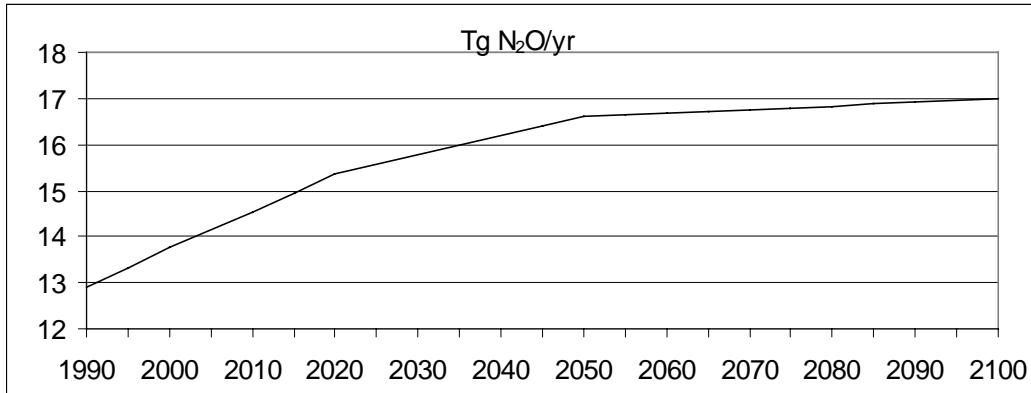


Figure 29: IS92a scenario for N₂O 1990-2100 (Tg/yr)

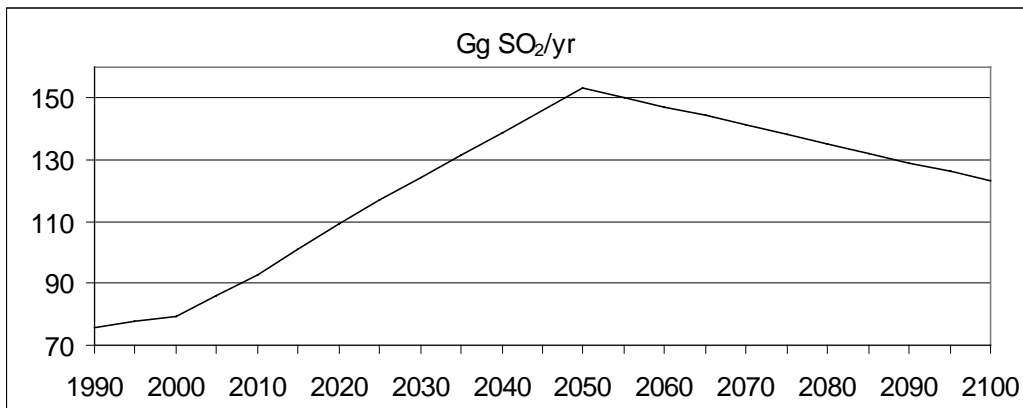


Figure 30: IS92a scenario for SO₂ 1990-2100 (Gg/yr)

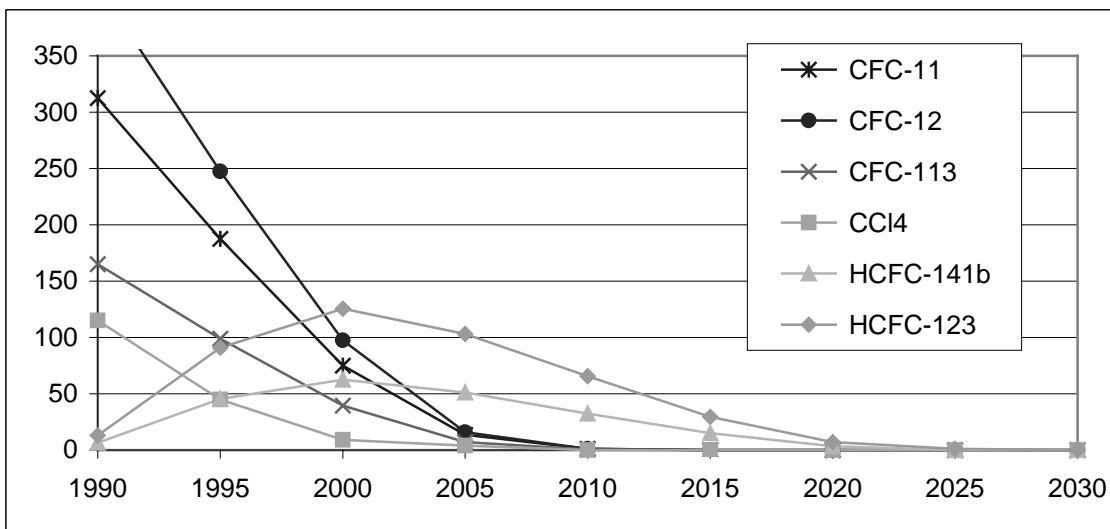


Figure 31: Copenhagen-like scenario for some halocarbons, 1990-2030 (Gg/yr)

Annex III: Tabular data

Table 6: Concentration of CO₂, CH₄ and N₂O 1750-1990. Source: see Table 4.

	CO ₂	CH ₄	N ₂ O		CO ₂	CH ₄	N ₂ O
	ppmv	ppbv	ppbv		ppmv	ppbv	ppbv
	CO ₂	CH ₄	N ₂ O		CO ₂	CH ₄	N ₂ O
1750	277.4	789.1	275.0				
1755	277.6	789.4	275.5	1875	290.2	913.3	287.9
1760	277.8	789.7	276.0	1880	291.2	924.7	288.4
1765	278.0	790.0	276.5	1885	292.4	936.7	288.9
1770	278.2	790.3	277.1	1890	293.7	949.1	289.4
1775	278.4	791.1	277.6	1895	295.0	962.0	289.9
1780	278.8	792.4	278.1	1900	296.2	975.4	290.4
1785	279.2	794.2	278.6	1905	297.5	989.4	291.0
1790	279.7	796.6	279.1	1910	299.0	1003.8	291.5
1795	280.3	799.4	279.6	1915	300.5	1018.8	292.0
1800	280.9	802.7	280.2	1920	302.1	1034.2	292.5
1805	281.6	806.6	280.7	1925	303.6	1050.2	293.0
1810	282.3	810.9	281.2	1930	305.1	1066.6	293.5
1815	283.0	815.8	281.7	1935	306.4	1083.6	294.1
1820	283.5	821.1	282.2	1940	307.8	1101.1	294.6
1825	284.0	827.0	282.7	1945	309.4	1121.7	295.1
1830	284.4	833.3	283.2	1950	311.4	1147.2	295.6
1835	285.0	840.2	283.8	1955	313.9	1177.7	296.1
1840	285.6	847.6	284.3	1960	317.0	1227.3	296.6
1845	286.3	855.5	284.8	1965	320.7	1299.9	297.7
1850	287.0	863.8	285.3	1970	325.7	1387.8	298.8
1855	287.6	872.7	285.8	1975	331.8	1483.3	300.7
1860	288.1	882.1	286.3	1980	338.9	1578.6	302.6
1865	288.6	892.0	286.8	1985	346.6	1660.3	306.1
1870	289.3	902.4	287.4	1990	354.4	1722.3	309.6

Table 7: Concentrations for GHGs 1950-1990 in pptv. Source: see Table 4.

	CFC-11	CFC-12	CFC-113	CFC-114	CFC-115	CCl ₄	CH ₃ CCl ₃
1950	0	0	0	0	0	0	0
1955	8.75	15.15	0	0	0	0	0
1960	17.5	30.3	0	0	0	0	0
1965	38.75	75.15	1	0.5	0	52.5	17.5
1970	60	120	2	1	0	105	35
1975	115	205	6	2	1	111	60
1980	173	295	15	4	2	118	85
1985	222	382	30	8	4	126	110
1990	263	477	77	19	5	133	133
	HCFC-22	HCFC-141b	HCFC-123	HCFC-142b	CF ₄	C ₂ F ₆	SF ₆
1950	0	0	0	0	44	0	0
1955	0	0	0	0	44	0	0
1960	0	0	0	0	44	0	0
1965	5	0	0	0	44	0	0
1970	10	0	0	0	49	0.5	0
1975	25	0	0	0.11	54	0.9	0.2
1980	50	0	0	0.25	59	1.3	0.8
1985	70	0	0	0.5	64	1.7	1.4
1990	91	2	0	1	69	2.1	2.15
	H-1211	H-1301	H-2402	CH ₃ Br	HFC-23		
1950	0	0	0	9.06	0		
1955	0	0	0	9.06	0		
1960	0	0	0	9.06	0		
1965	0	0	0	9.06	0.85		
1970	0.1	0.1	0.01	9.06	1.7		
1975	0.2	0.2	0.05	9.06	2.55		
1980	0.5	0.6	0.12	9.06	3.4		
1985	1.5	1.7	0.23	9.06	5.2		
1990	2.5	3.5	0.37	9.06	7.6		

Table 8: Emissions of carbon and anthropogenic sulphur 1750-1990. Source: See Table 4.

Year	Carbon Emissions		Sulphur Emission s	Year	Carbon Emissions		Sulphur Emission s
	Land-use change	Fossil fuel burning			Land-use change	Fossil fuel burning	
	GtC	GtC	Tg S		GtC	GtC	Tg S
1750	0.155	0	0	1786	0.258	0	0
1751	0.158	0	0	1787	0.261	0	0
1752	0.161	0	0	1788	0.264	0	0
1753	0.164	0	0	1789	0.267	0	0
1754	0.167	0	0	1790	0.269	0	0
1755	0.17	0	0	1791	0.272	0	0
1756	0.173	0	0	1792	0.275	0	0
1757	0.176	0	0	1793	0.278	0	0
1758	0.179	0	0	1794	0.28	0	0
1759	0.182	0	0	1795	0.283	0	0
1760	0.185	0	0	1796	0.286	0	0
1761	0.188	0	0	1797	0.289	0	0
1762	0.191	0	0	1798	0.292	0	0
1763	0.194	0	0	1799	0.294	0	0
1764	0.197	0	0	1800	0.297	0	0
1765	0.2	0	0	1801	0.3	0	0
1766	0.203	0	0	1802	0.303	0	0
1767	0.206	0	0	1803	0.305	0	0
1768	0.208	0	0	1804	0.308	0	0
1769	0.211	0	0	1805	0.311	0	0
1770	0.214	0	0	1806	0.314	0	0
1771	0.217	0	0	1807	0.316	0	0
1772	0.219	0	0	1808	0.319	0	0
1773	0.222	0	0	1809	0.322	0	0
1774	0.225	0	0	1810	0.325	0	0
1775	0.228	0	0	1811	0.328	0	0
1776	0.231	0	0	1812	0.33	0	0
1777	0.233	0	0	1813	0.333	0	0
1778	0.236	0	0	1814	0.336	0	0
1779	0.239	0	0	1815	0.339	0	0
1780	0.242	0	0	1816	0.341	0	0
1781	0.244	0	0	1817	0.344	0	0
1782	0.247	0	0	1818	0.347	0	0
1783	0.25	0	0	1819	0.35	0	0
1784	0.253	0	0	1820	0.353	0	0
1785	0.255	0	0	1821	0.355	0	0
				1822	0.358	0	0

Table 8 continued

Year	Carbon Emissions		Sulphur
	Land-use	Fossil fuel	Emission s
	change	burning	
	GtC	GtC	Tg S
1823	0.361	0	0
1824	0.364	0	0
1825	0.366	0	0
1826	0.369	0	0
1827	0.372	0	0
1828	0.375	0	0
1829	0.377	0	0
1830	0.38	0	0
1831	0.383	0	0
1832	0.386	0	0
1833	0.389	0	0
1834	0.391	0	0
1835	0.394	0	0
1836	0.397	0	0
1837	0.4	0	0
1838	0.402	0	0
1839	0.405	0	0
1840	0.408	0	0
1841	0.411	0	0
1842	0.414	0	0
1843	0.416	0	0
1844	0.419	0	0
1845	0.422	0.006	0
1846	0.425	0.012	0
1847	0.427	0.017	0
1848	0.43	0.023	0
1849	0.433	0.029	0
1850	0.436	0.035	0
1851	0.468	0.041	0.25
1852	0.482	0.047	0.5
1853	0.494	0.053	0.75
1854	0.504	0.058	1
1855	0.512	0.064	1.25
1856	0.519	0.07	1.5
1857	0.525	0.076	1.75
1858	0.53	0.082	2
1859	0.534	0.087	2.25

Year	Carbon Emissions		Sulphur
	Land-use	Fossil fuel	Emission s
	change	burning	
	GtC	GtC	Tg S
1860	0.542	0.093	2.5
1861	0.534	0.099	2.64
1862	0.539	0.098	2.78
1863	0.544	0.106	2.92
1864	0.549	0.115	3.06
1865	0.554	0.122	3.2
1866	0.557	0.129	3.34
1867	0.56	0.138	3.48
1868	0.564	0.137	3.62
1869	0.569	0.142	3.76
1870	0.572	0.145	3.9
1871	0.582	0.162	4.12
1872	0.588	0.176	4.34
1873	0.592	0.188	4.56
1874	0.596	0.184	4.78
1875	0.6	0.189	5
1876	0.605	0.192	5.22
1877	0.607	0.196	5.44
1878	0.609	0.197	5.66
1879	0.61	0.208	5.88
1880	0.611	0.227	6.1
1881	0.642	0.244	6.42
1882	0.656	0.263	6.74
1883	0.663	0.28	7.06
1884	0.668	0.282	7.38
1885	0.673	0.276	7.7
1886	0.677	0.279	8.02
1887	0.678	0.298	8.34
1888	0.679	0.322	8.66
1889	0.679	0.329	8.98
1890	0.687	0.35	9.3
1891	0.684	0.365	9.78
1892	0.685	0.369	10.26
1893	0.684	0.362	10.74
1894	0.683	0.377	11.22
1895	0.682	0.399	11.7
1896	0.68	0.412	12.18

Table 8 continued

Year	Carbon Emissions		Sulphur
	Land-use	Fossil fuel	Emission s
	change	burning	
GtC	GtC	Tg S	
1897	0.68	0.431	12.66
1898	0.681	0.455	13.14
1899	0.683	0.497	13.62
1900	0.686	0.525	14.1
1901	0.749	0.54	14.82
1902	0.767	0.553	15.54
1903	0.782	0.606	16.26
1904	0.795	0.613	16.98
1905	0.806	0.647	17.7
1906	0.817	0.696	18.42
1907	0.822	0.771	19.14
1908	0.825	0.737	19.86
1909	0.827	0.768	20.58
1910	0.828	0.805	21.3
1911	0.773	0.822	21.48
1912	0.757	0.866	21.66
1913	0.746	0.929	21.84
1914	0.743	0.838	22.02
1915	0.734	0.831	22.2
1916	0.737	0.895	22.76
1917	0.736	0.945	23.32
1918	0.736	0.932	23.88
1919	0.736	0.829	24.44
1920	0.736	0.959	25
1921	0.785	0.828	25.02
1922	0.799	0.891	25.04
1923	0.811	1.005	25.06
1924	0.817	0.999	25.08
1925	0.827	1.006	25.1
1926	0.825	1.006	25.5
1927	0.824	1.097	25.9
1928	0.805	1.09	26.3
1929	0.78	1.172	26.7
1930	0.775	1.077	27.1
1931	0.783	0.968	26.6
1932	0.779	0.874	26.1
1933	0.774	0.919	25.6
1934	0.768	0.997	25.1
1935	0.762	1.032	24.6
1936	0.767	1.146	26.22
1937	0.765	1.226	27.84
1938	0.762	1.161	29.46
1939	0.757	1.233	31.08
1940	0.751	1.3	32.7
1941	0.73	1.337	31.72
1942	0.723	1.334	30.74
1943	0.716	1.364	29.76
1944	0.712	1.352	28.78
1945	0.709	1.203	27.8
1946	0.758	1.271	29.6
1947	0.768	1.421	31.4
1948	0.774	1.517	33.2
1949	0.776	1.485	35
1950	0.782	1.638	36.8
1951	0.946	1.775	37.42
1952	0.987	1.803	38.04
1953	0.992	1.848	38.66
1954	1.089	1.871	39.28
1955	1.126	2.05	39.9
1956	1.155	2.185	41.9
1957	1.091	2.278	43.9
1958	1.083	2.338	45.95
1959	1.087	2.471	48
1960	1.085	2.586	48.6
1961	1.232	2.602	49.2
1962	1.271	2.708	50.9
1963	1.309	2.855	52.6
1964	1.339	3.016	53.95
1965	1.363	3.154	55.3
1966	1.333	3.314	55.9
1967	1.332	3.42	56.5
1968	1.345	3.596	58
1969	1.35	3.809	59.5
1970	1.297	4.084	62

Table 8 continued

Year	Carbon Emissions		Sulphur Emission s
	Land-use change	Fossil fuel burning	
	GtC	GtC	Tg S
1971	1.277	4.235	64.5
1972	1.246	4.403	65.75
1973	1.279	4.641	67
1974	1.259	4.649	68
1975	1.255	4.622	69
1976	1.339	4.889	70.5
1977	1.363	5.028	72
1978	1.363	5.076	71
1979	1.404	5.358	73
1980	1.415	5.29	72
1981	1.435	5.119	70
1982	1.479	5.08	71
1983	1.51	5.07	71
1984	1.567	5.242	74
1985	1.596	5.417	76
1986	1.661	5.609	78
1987	1.694	5.736	79
1988	1.711	5.961	81
1989	1.705	6.07	83
1990	1.713	6.099	85

Table 9: Emission scenarios for GHGs 1990-2100 in Gg/yr unless other indicated. Source: see table 2.

	Pg C	Tg CH₄	Tg N₂O	Gg SO₂	CFC-11	CFC-12	CFC-113
1990	7.4	506.1	12.9	75.9	312.5	412.5	165.0
1995	7.9	525.3	13.3	77.6	187.5	247.5	99.0
2000	8.4	544.5	13.8	79.4	75.0	97.5	39.5
2005	9.2	566.4	14.1	86.2	13.5	16.0	7.0
2010	9.9	588.2	14.5	93.0	1.0	1.0	0.5
2015	10.6	609.9	14.9	101.2	0.0	0.0	0.0
2020	11.4	631.7	15.4	109.5	0.0	0.0	0.0
2025	11.9	657.2	15.6	116.8	0.0	0.0	0.0
2030	12.4	682.8	15.8	124.2	0.0	0.0	0.0
2035	13.0	708.3	16.0	131.5	0.0	0.0	0.0
2040	13.5	733.8	16.2	138.8	0.0	0.0	0.0
2045	14.0	759.4	16.4	146.1	0.0	0.0	0.0
2050	14.5	784.9	16.6	153.4	0.0	0.0	0.0
2055	15.1	798.1	16.7	150.4	0.0	0.0	0.0
2060	15.7	811.3	16.7	147.3	0.0	0.0	0.0
2065	16.3	824.5	16.7	144.3	0.0	0.0	0.0
2070	16.8	837.7	16.8	141.3	0.0	0.0	0.0
2075	17.4	850.9	16.8	138.2	0.0	0.0	0.0
2080	18.0	864.1	16.8	135.2	0.0	0.0	0.0
2085	18.6	877.3	16.9	132.2	0.0	0.0	0.0
2090	19.1	890.5	16.9	129.2	0.0	0.0	0.0
2095	19.7	903.7	16.9	126.1	0.0	0.0	0.0
2100	20.3	916.9	17.0	123.1	0.0	0.0	0.0

Emission scenarios for GHGs 1990-2100 in Gg/yr (continued).

	CFC-114	CFC-115	CCl ₄	CH ₃ CCl ₃	HCFC-22	HCFC-141b	HCFC-123	HCFC-124
1990	6	16.5	115	720	218.5	6.5	13	0
1995	6	9.5	45	320	419.5	45.5	91	3.5
2000	3.5	3.5	9	87	502	62.5	125.5	7
2005	0.5	0.5	4	30	433.5	51	103	7.8
2010	0	0	0	3	282.5	32.5	65.5	8.6
2015	0	0	0	0	117.5	15	29.5	9.4
2020	0	0	0	0	28	3.5	7	10.2
2025	0	0	0	0	3	0	1	11
2030	0	0	0	0	0	0	0	11.8
2035	0	0	0	0	0	0	0	12.6
2040	0	0	0	0	0	0	0	13.4
2045	0	0	0	0	0	0	0	14.2
2050	0	0	0	0	0	0	0	15
2055	0	0	0	0	0	0	0	15.1
2060	0	0	0	0	0	0	0	15.2
2065	0	0	0	0	0	0	0	15.3
2070	0	0	0	0	0	0	0	15.4
2075	0	0	0	0	0	0	0	15.5
2080	0	0	0	0	0	0	0	15.6
2085	0	0	0	0	0	0	0	15.7
2090	0	0	0	0	0	0	0	15.8
2095	0	0	0	0	0	0	0	15.9
2100	0	0	0	0	0	0	0	16

Emission scenarios for GHGs 1990-2100 in Gg/yr (continued).

	HCFC-142b	HCFC-225ca/cb	HFC-134a	HFC-125	HFC-152a	CF₄	C₂F₆	SF₆
1990	0	2.5	0	0	0	20	1.3	5.5
1995	3.5	5.5	74	0	0	20	1.3	6.4
2000	7	8.5	148	0	0	20	1.3	6.8
2005	7.8	9.8	211.8	2.8	6	20	1.3	6.8
2010	8.6	11.1	275.6	5.6	12	20	1.3	6.8
2015	9.4	12.4	339.4	8.4	18	20	1.3	6.8
2020	10.2	13.7	403.2	11.2	24	20	1.3	6.8
2025	11	15	467	14	30	20	1.3	6.8
2030	8.8	15.8	557.2	46.2	113.6	20	1.3	6.8
2035	6.6	16.6	647.4	78.4	197.2	20	1.3	6.8
2040	4.4	17.4	737.6	110.6	280.8	20	1.3	6.8
2045	2.2	18.2	827.8	142.8	364.4	20	1.3	6.8
2050	0	19	918	175	448	20	1.3	6.8
2055	0	19.1	931.7	177.4	460.2	20	1.3	6.8
2060	0	19.2	945.4	179.8	472.4	20	1.3	6.8
2065	0	19.3	959.1	182.2	484.6	20	1.3	6.8
2070	0	19.4	972.8	184.6	496.8	20	1.3	6.8
2075	0	19.5	986.5	187	509	20	1.3	6.8
2080	0	19.6	1000.2	189.4	521.2	20	1.3	6.8
2085	0	19.7	1013.9	191.8	533.4	20	1.3	6.8
2090	0	19.8	1027.6	194.2	545.6	20	1.3	6.8
2095	0	19.9	1041.3	196.6	557.8	20	1.3	6.8
2100	0	20	1055	199	570	20	1.3	6.8

Emission scenarios for GHGs 1990-2100 in Gg/yr (continued).

	H-1211	H-1301	H-2402	CH₃Br	HFC-23
1990	3.0	4.0	1.8	206.0	5.9
1995	4.5	4.0	1.8	206.0	9.8
2000	6.0	4.0	0.6	200.8	13.6
2005	7.5	3.5	0.2	181.4	10.7
2010	9.0	3.0	0.1	181.4	7.7
2015	6.3	2.7	0.0	167.0	5.1
2020	3.7	2.3	0.0	167.0	2.6
2025	1.0	2.0	0.0	167.0	0.1
2030	0.8	1.6	0.0	167.0	0.1
2035	0.6	1.2	0.0	167.0	0.0
2040	0.4	0.8	0.0	167.0	0.0
2045	0.2	0.4	0.0	167.0	0.0
2050	0.0	0.0	0.0	167.0	0.0
2055	0.0	0.0	0.0	167.0	0.0
2060	0.0	0.0	0.0	167.0	0.0
2065	0.0	0.0	0.0	167.0	0.0
2070	0.0	0.0	0.0	167.0	0.0
2075	0.0	0.0	0.0	167.0	0.0
2080	0.0	0.0	0.0	167.0	0.0
2085	0.0	0.0	0.0	167.0	0.0
2090	0.0	0.0	0.0	167.0	0.0
2095	0.0	0.0	0.0	167.0	0.0
2100	0.0	0.0	0.0	167.0	0.0

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