

ANNEX

Climatic consequences of emissions

Model calculations contributed by:

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A.1 Introduction

Modelling studies have been undertaken by a number of research groups to investigate the climate consequences of several man-made emission scenarios. The first category of emission scenarios is that generated by IPCC Working Group III, which represents a broad range of possible controls to limit the emissions of greenhouse gases, these we refer to as **policy scenarios**. The second category of scenarios is generated by Working Group I to illustrate the way in which the atmosphere and climate would respond to changes in emissions, these we refer to as **science scenarios**. Many of the results have already been displayed in the appropriate sections of this report, they are brought together here to allow the complete emissions-climate pathway to be seen. The exploration of the climate consequences of both categories of emissions scenarios involved the sequence of modelling studies illustrated in Figure A.1

A.1.1 Policy Scenarios

Four policy scenarios have been developed by Working Group III, they are described in Appendix 1 of this report

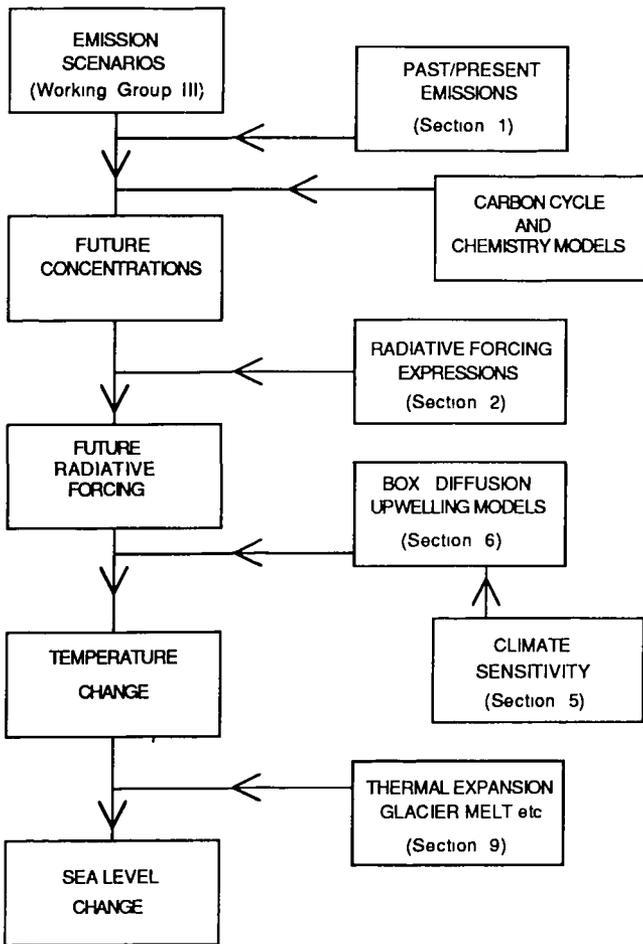


Figure A.1: Sequence of modelling studies

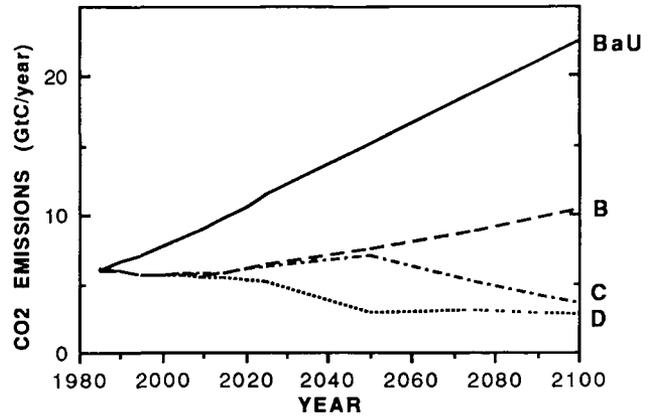


Figure A.2(a): Emissions of carbon dioxide (as an example) in the four policy scenarios generated by IPCC Working Group III

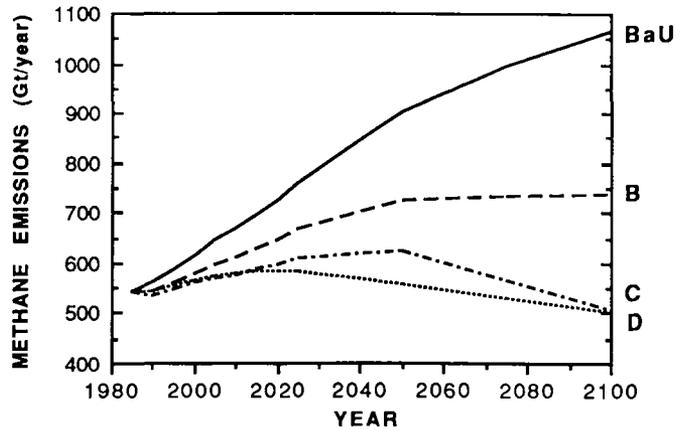


Figure A.2(b): Emissions of methane (as an example) in the four policy scenarios generated by IPCC Working Group III

The first approximates to a Business-as-Usual (BaU) case. The other three incorporate a progressive penetration of controls on greenhouse gas emissions, and in this report are labelled Scenario B, C and D (The BaU case had earlier been referred to as Scenario A)

Each scenario includes emissions of the main greenhouse gases, and other gases (such as NO_x and CO) which influence their concentrations. The emissions of carbon dioxide and methane are shown in Figure A.2 as examples. For further information on the background to and method of generation of, these policy scenarios, see Expert Group on Emissions Scenarios (1990)

A.1.2 Science Scenarios

The chain of processes in the atmosphere and other components of the climate system which lead from emissions to climate change (typified in this case by global temperature and sea level rise) can be illustrated by using a

small number of cases where emissions are changed in some hypothetical manner, often exaggerated for clarity. The following science scenarios were selected by Working Group I: changes described apply equally to all the greenhouse gases.

- S1 Constant emissions at 1990 levels of all gases from 1990 onwards,
- S2 Reduce all emissions by 50% in 1990, and hold constant thereafter,
- S3 Decrease emissions at 2% per year compound from 1990,
- S4 Increase emissions at 2% per year compound until 2010, then decrease at 2% per year compound.

In each case the 1990 emissions are assumed to be those given in the Business-as-Usual policy scenario.

A.2 Pre-1990 Greenhouse Gas Concentrations

Concentrations of the greenhouse gases prior to 1989 are taken as those observed directly in the atmosphere or in ice-cores, as discussed in Section 1. The year 1765 was chosen as the pre-industrial baseline for greenhouse gas concentrations (and, hence, for man-made forcing and global mean temperature). 1990 concentrations were calculated by making a small extrapolation from most recent observations and trends.

A.3 Future Greenhouse Gas Concentrations

A number of models which contain representations of atmospheric chemistry and the carbon cycle have been used to make projections of future atmospheric concentrations of the greenhouse gases from the man-made emissions scenarios. The results from each of the models are not shown explicitly. For each scenario and gas, a single best-estimate was made of the concentration projection, and these are shown in Figure A.3 for the policy scenarios and A.4–A.5 for the science scenarios. In most cases these best estimates were simple means of a number of model results.

A quantitative understanding of the relationship between trace gas emissions and tropospheric concentrations requires a description in three dimensions of atmospheric dynamics, atmospheric chemistry and sources and sinks. The problem is complex and demands the use of large supercomputers. Hence the results described in this Annex have been obtained with models which contain a number of simplifying assumptions. The models give a range of future concentrations depending on the assumptions adopted. Tropospheric models together with their representations of

atmospheric transport and chemistry have not been subject to comparison and evaluation in the same manner as the stratospheric assessment models. Consequently, there are no favoured approaches or recommended models.

In many cases, comparison of different model results reveal many shortcomings in the emissions scenarios themselves. Each emission scenario starts from 1985 and extends to 2100. Much is known about trace gas sources and sinks from these and other modelling studies of the 1985 atmosphere. The current emissions provided by Working Group III (WGIII) have not always been harmonised with previous model studies of the life cycles of these trace gases. Each set of model studies has therefore been adjusted in some way to accommodate the 1985 situation where the emissions are in some way inadequate.

Emissions of some gases, in particular man-made and natural hydrocarbons, were not projected by WGIII, each modelling group has therefore made its own assumptions about these, and this is an additional cause of differences between model results.

In the case of **nitrous oxide**, its atmospheric burden and its rate of increase have been well established from observations and the models have been set up to reproduce these observations. The lifetime calculated within each model determines the 1985 emissions required to support the current atmospheric burden and its rate of increase. There is a narrow range of emissions which satisfies this balance and it is model dependent, the WGIII emissions do not in general fall within this range, and modelling groups have therefore adopted one of two approaches to correct for this.

The WGIII emissions, taken together with current atmospheric concentration and its rate of increase, yield a lifetime of 167 years, somewhat longer than that generally accepted (see Section 1.5). Models with shorter lifetimes than 167 years will not reproduce current rate of increase of concentration, and some modellers have added further nitrous oxide emissions in order to accommodate this, this has led to a divergence between model results.

The 1985 atmospheric concentration of **methane** is well known, and its rate of increase shows that sources and sinks are not currently in balance. Not all aspects of these methane sources have yet been adequately quantified, neither has the sink through its reaction with OH. Whilst the accuracies in sources and sinks are adequate in budget studies to confirm that tropospheric OH can indeed account for the observed methane behaviour, the lack of accuracy has led to problems in the concentration calculations described here.

The atmospheric burden of methane and its rate of increase have been well established from observations and the models have been set up to reproduce them. The OH radical concentration distribution calculated within each model determines the 1985 emissions required to support

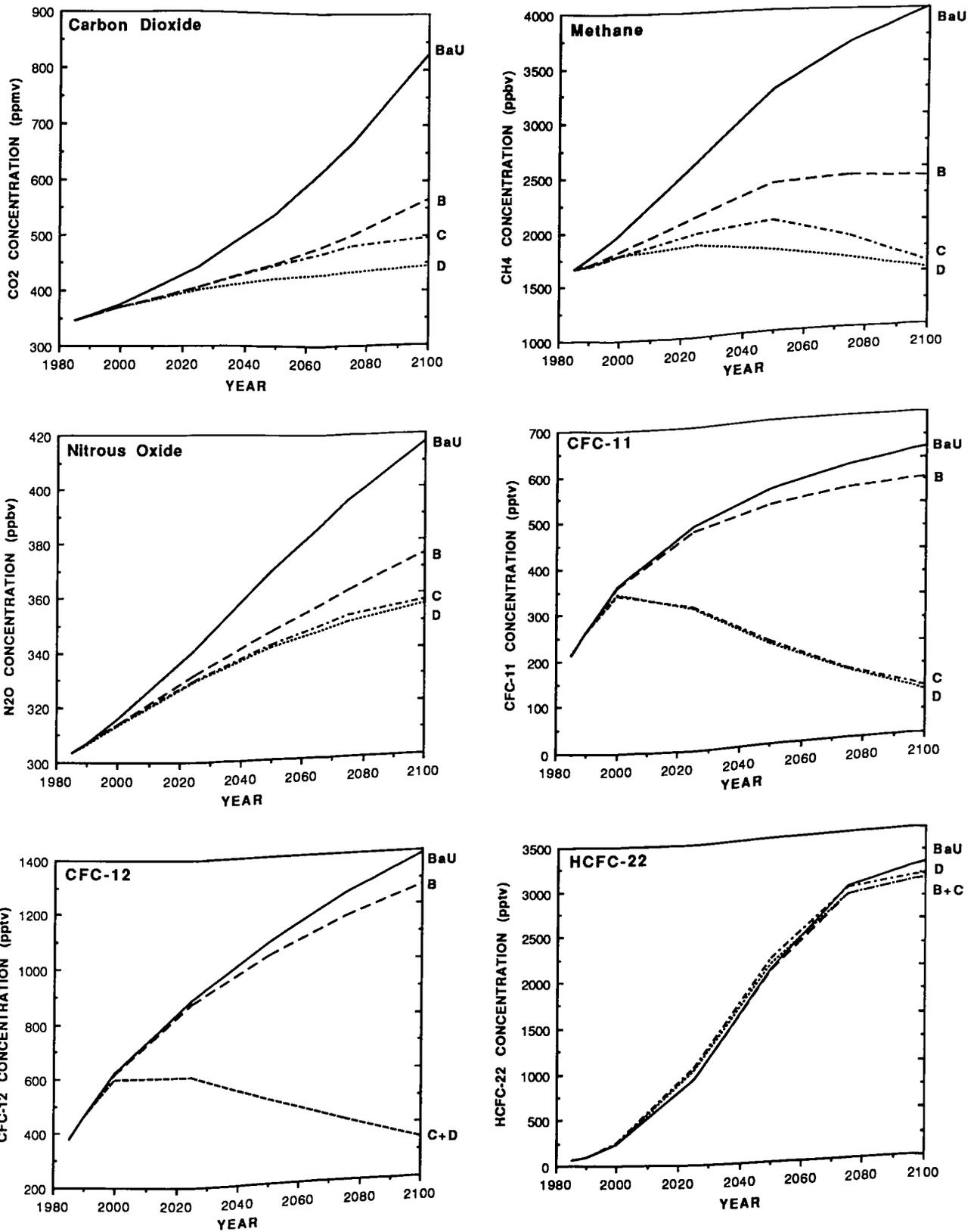


Figure A.3: Concentrations of the main man made greenhouse gases resulting from the four IPCC WGIII "policy" emissions scenarios

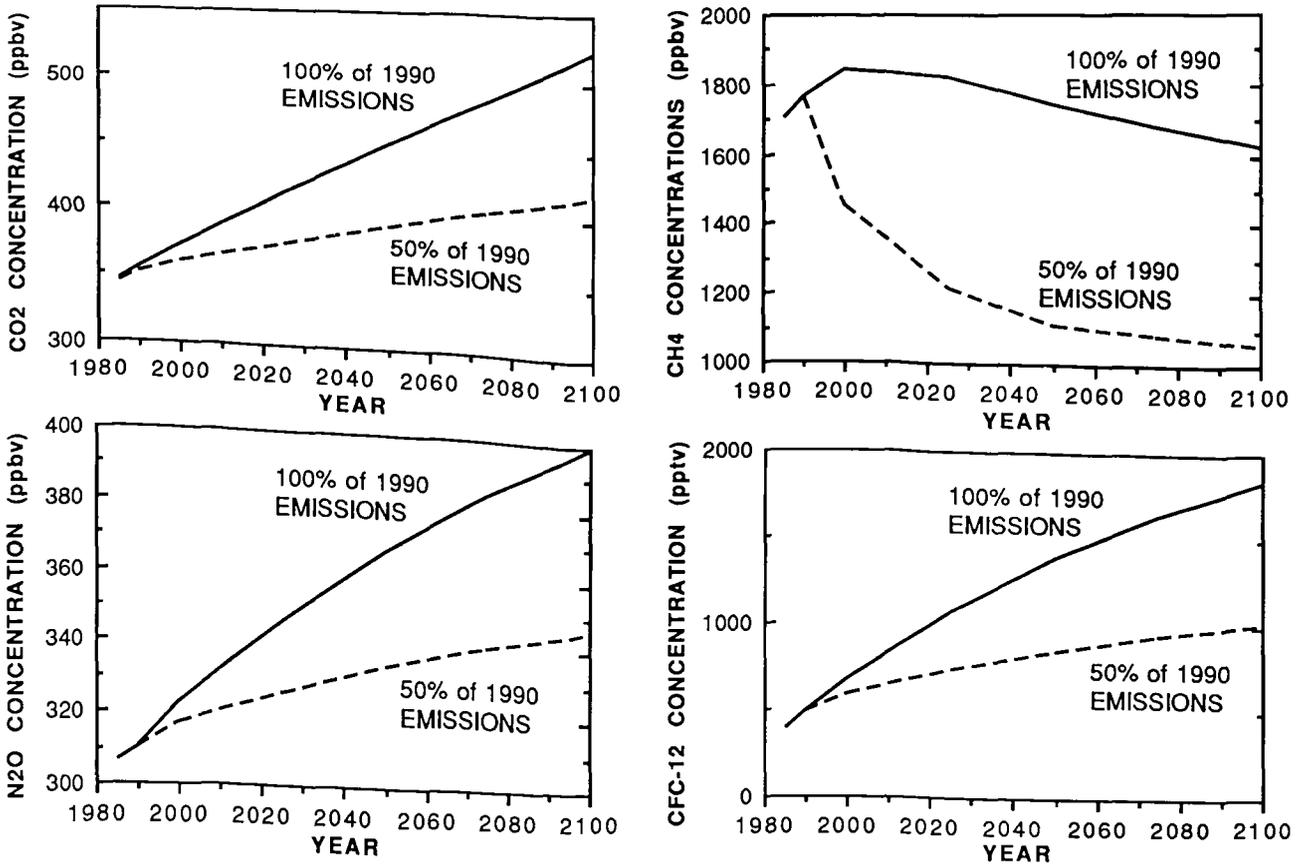


Figure A.4: Concentrations of carbon dioxide, methane, nitrous oxide and CFC-12 resulting from continuing emissions at 100% of 1990 levels, and emissions at 50% of 1990 levels

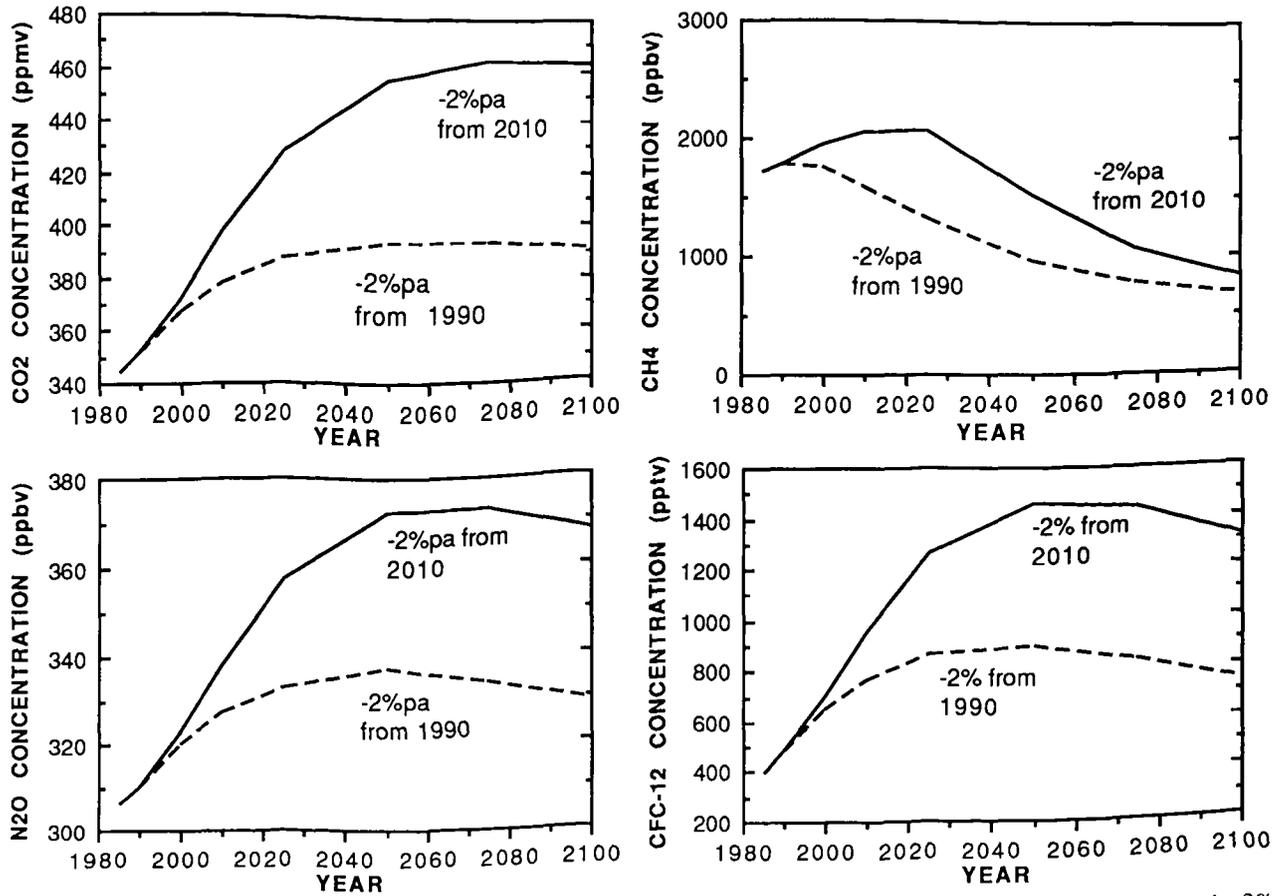


Figure A.5: Concentrations of carbon dioxide, methane, nitrous oxide and CFC-12 resulting from (a) decreasing emissions by 2% pa from 1990, and (b) increasing emissions by 2% pa until 2010, followed by decreasing emissions at 2% pa

the current atmospheric burden and its rate of increase. There is a narrow, model dependent, range of methane, carbon monoxide and oxides of nitrogen emissions which satisfies this balance. The 1985 emissions provided in the scenarios do not fall within the required range of all the models, and modellers have therefore adopted one of two approaches, causing the part of divergence in model results. Some models have used the methane, carbon monoxide and NO_x emission scenarios exactly as provided and scaled up all their results to make the 1985 methane concentrations agree with observations. Other models have added extra methane, carbon monoxide or NO_x to make the 1985 methane concentrations agree with observations and maintained the extra injection throughout each calculation.

Differences in results can also arise because each model calculates a different scenario- and time-dependent tropospheric OH distribution. One model includes a feedback between composition changes to temperature changes to relative humidity changes back to OH radical concentrations. Almost all the models include the complex interaction between the future methane, carbon monoxide, ozone and nitrogen oxides concentrations on future OH radical concentrations.

CFCs 11 and 12 both have well quantified sources and stratospheric photolytic sinks. The relatively small differences between model calculations is due to differences in model transport and assumed or calculated atmospheric lifetimes. Such differences are similar to those reported in stratospheric ozone assessments (e.g., WMO, 1989).

Although **HCFC-22** sources are also all man-made its lifetime is determined not by stratospheric photolysis but by tropospheric OH oxidation. However, the temperature dependence of the oxidation reaction is so large that virtually all of the atmospheric removal occurs in low latitudes in the lower region of the troposphere and in the upper stratosphere. The models used for this assessment generally have different 1985 tropospheric OH radical distributions and the different model formulations lead to different future OH distributions depending on the methane, carbon monoxide and nitrogen oxide emissions. In addition, one of the models employed includes an additional feedback whereby future global warming leads to increased humidities and hence increased tropospheric OH radical concentrations. Longer lifetimes imply greater tropospheric build-up of HCFC-22 by the year 2100.

Several modelling groups calculated future concentrations of tropospheric and stratospheric **ozone**, but because there was a wide divergence in the results, and because the relationship between concentration and forcing is not well established, the effects of ozone have not yet been included in the climate response.

A.4 Past and Future Radiative Forcing

The relationships between atmospheric concentration and radiative forcing derived in Section 2 were applied to the concentration histories of the greenhouse gases described

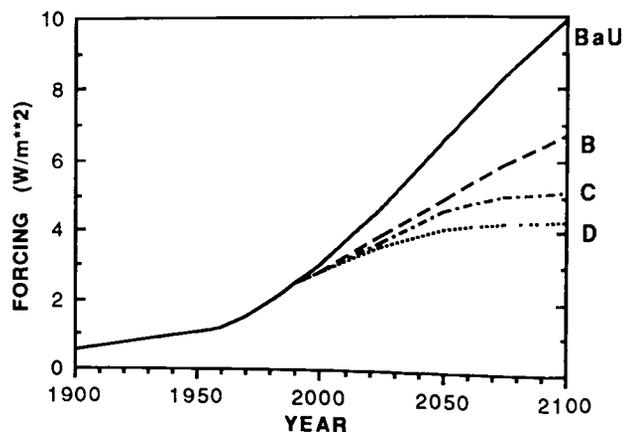


Figure A.6: Radiative forcing calculated from the four policy emissions scenarios

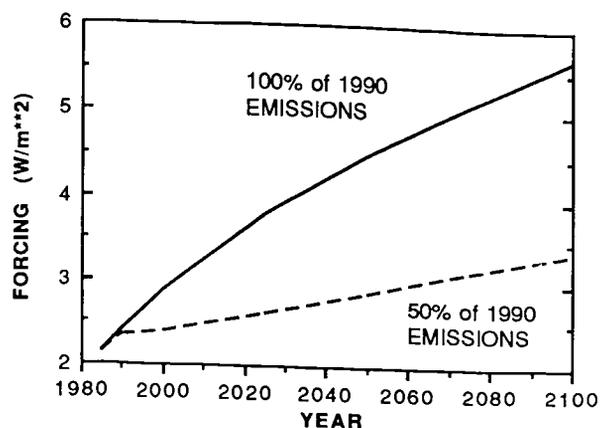


Figure A.7: Radiative forcing calculated to arise from continuing emissions of all man made greenhouse gases at 100% of 1990 levels and 50% of 1990 levels

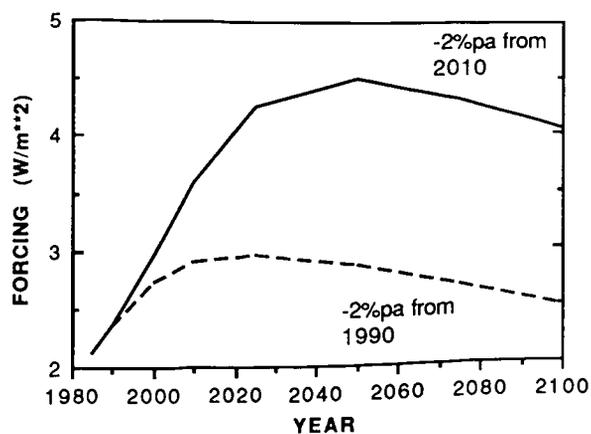


Figure A.8: Radiative forcing calculated to arise from (a) decreasing emissions of all man made greenhouse gases by 2% pa from 1990 and (b) increasing emissions of all gases by 2% pa until 2010 followed by decreasing emissions at 2% pa

above, and to the estimates of future concentrations from the four policy scenarios. The combined historical and future radiative forcing is illustrated for the four policy scenarios in Figure A.6, and those from the science scenarios in Figures A.7 and A.8.

A.5 Estimates of Future Global Mean Temperature

Ideally, the complete climate effects of the emission scenarios would be investigated using a comprehensive coupled atmosphere-ocean General Circulation Model, the results from which (using simple concentration increases) have been discussed in Section 6.4. Such model runs are prohibitively expensive and time consuming. Instead, estimates of the change in global mean surface air temperature due to man-made forcing (both historical and projected) were made using a box-diffusion-upwelling model of the type discussed in Section 6.6.

These models have a number of prescribed parameters (mixed-layer depth, upwelling rate, etc.) which are set to the optimum values discussed in Section 6. For each scenario, three values of climate sensitivity (the equilibrium temperature rise due to a doubling of carbon dioxide concentrations) are employed, as described in Section 5; 1.5°C, 2.5°C and 4.5°C. Results are given for each of these climate sensitivities, indicated as "high", "best estimate" and "low" in the figures.

Temperature rise estimates for the four policy scenarios are shown in Figure A.9, and those from the science scenarios are given in Figure A.10 and A.11 (best-estimate values only).

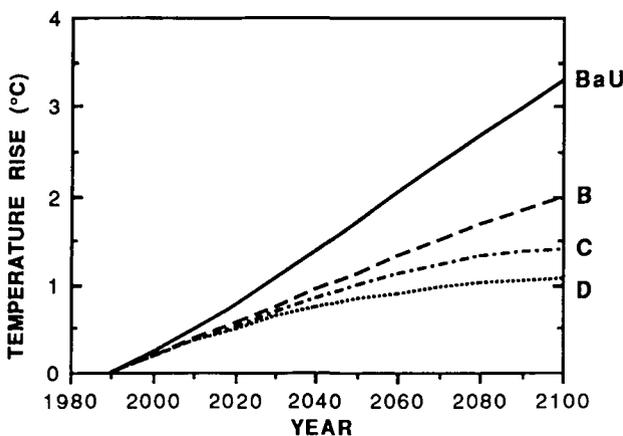


Figure A.9: Temperature rise calculated using a box-diffusion-upwelling model, due to the four IPCC WGIII "policy" emissions scenarios. Only the best-estimate value (corresponding to a climate sensitivity of 2.5°C) is shown.

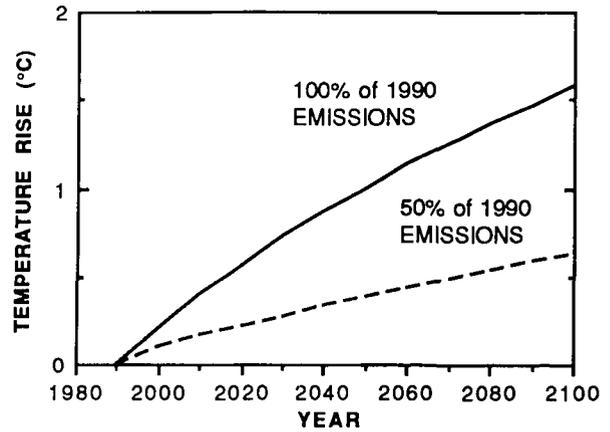


Figure A.10: Temperature rise calculated from continuing emissions of all man-made greenhouse gases at 100% of 1990 levels and 50% of 1990 levels.

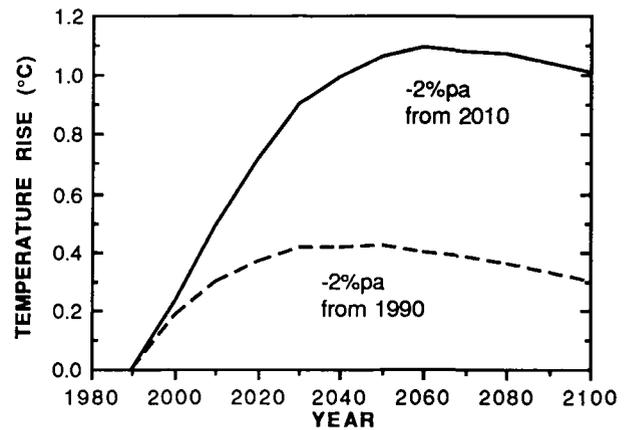


Figure A.11: Temperature rise calculated from (a) decreasing emissions of all man-made greenhouse gases by 2% pa from 1990, and (b) increasing emissions of all gases by 2%pa until 2010, followed by decreasing emissions at 2%pa.

A.6 Estimates of Future Global Mean Sea Level Rise

Box diffusion models are also used to estimate the sea level rise from the forcing projections; the thermal expansion part of future sea level rise is calculated directly by these models. The models also contain expressions for the contributions to sea level change from glacier and land ice melting, and changes in the mass-balance of the Greenland and Antarctic ice sheets.

Sea level changes estimated from the four policy scenarios are shown in Figure A.12, and for the science scenarios in Figure A.13 and A.14. Again, "high", "best-estimate" and "low" curves are shown for the policy scenarios, corresponding to the same climate sensitivities as used in the temperature rise estimates.

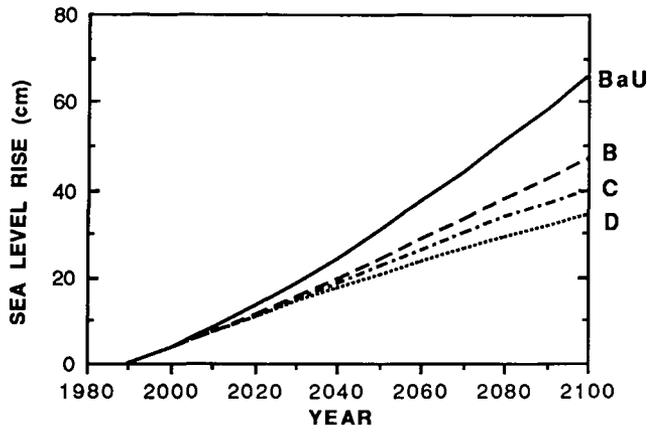


Figure A.12: Sea level rise due to the four IPCC WGIII 'policy' emissions scenarios. Only the best-estimate value (corresponding to a climate sensitivity of 2.5°C) is shown.

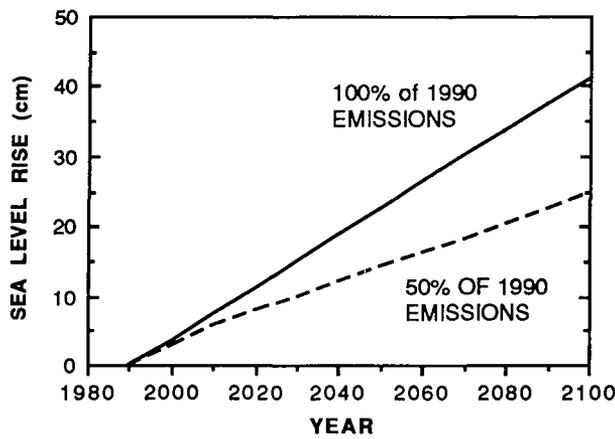


Figure A.13: Sea level rise calculated from continuing emissions of all man-made greenhouse gases at 100% of 1990 levels and 50% of 1990 levels.

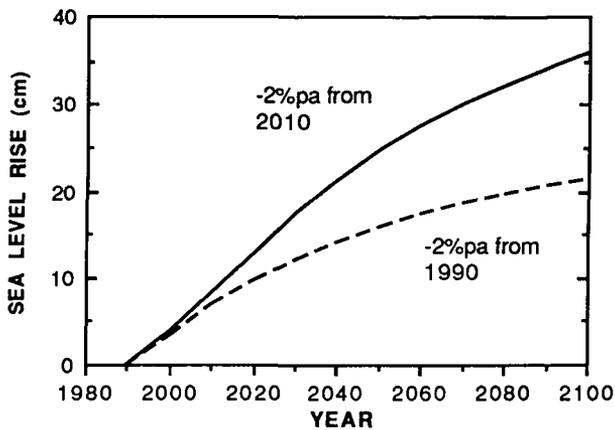


Figure A.14: Sea level rise calculated from (a) decreasing emissions of all man-made greenhouse gases by 2% per annum from 1990, and (b) increasing emissions of all gases by 2% per annum until 2010, followed by decreasing emissions at 2% per annum.

A.7 Emissions to Sea Level Rise Pathway for Science Scenarios

In order to illustrate the timescales for adjustment of the climate to changes in emissions, the full pathway between emission change, through concentration change (using carbon dioxide as an example), radiative forcing, temperature rise and sea level rise is illustrated for each of the science scenarios in Figures A.15 to A.18.

References

Expert Group on Emissions Scenarios, IPCC Working Group III, Draft Report on Emissions Scenarios, February 1990
 WMO, 1989. Scientific Assessment of stratospheric ozone 1989, Global Ozone Research and Monitoring Project, Report 20, Geneva.

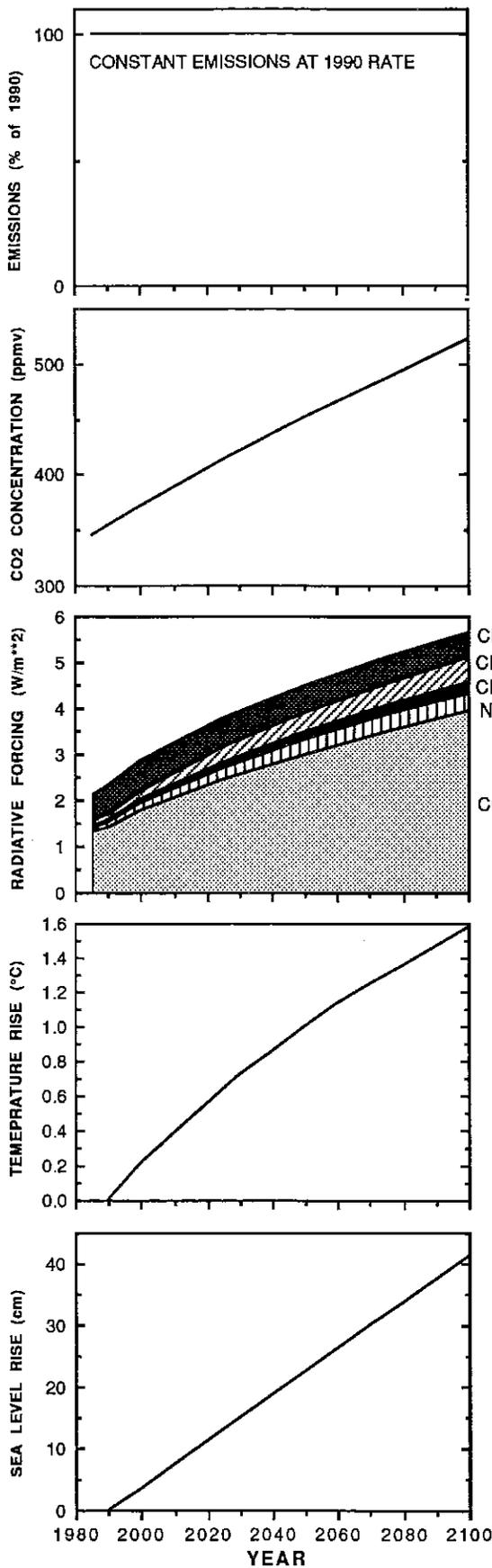


Figure A.15: The complete emissions- sea level rise pathway shown in the case of continuing emissions at 1990 levels.

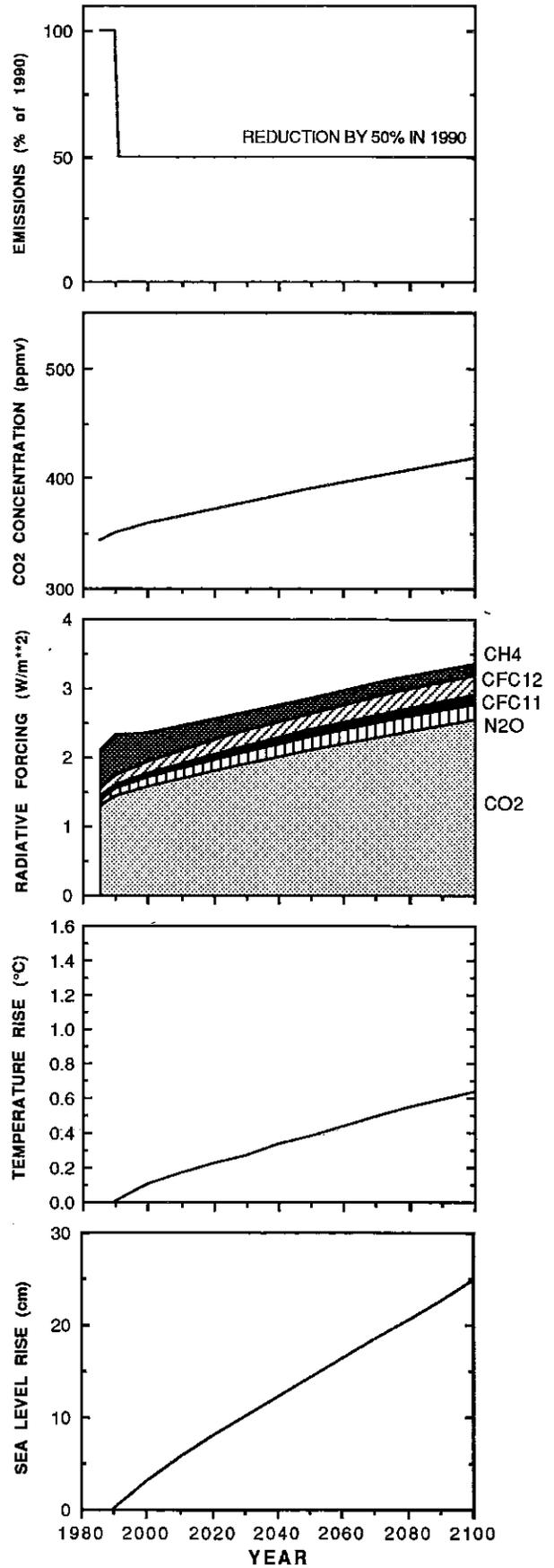


Figure A.16: The complete emissions- sea level rise pathway shown for emissions continuing at 50% of 1990 levels.

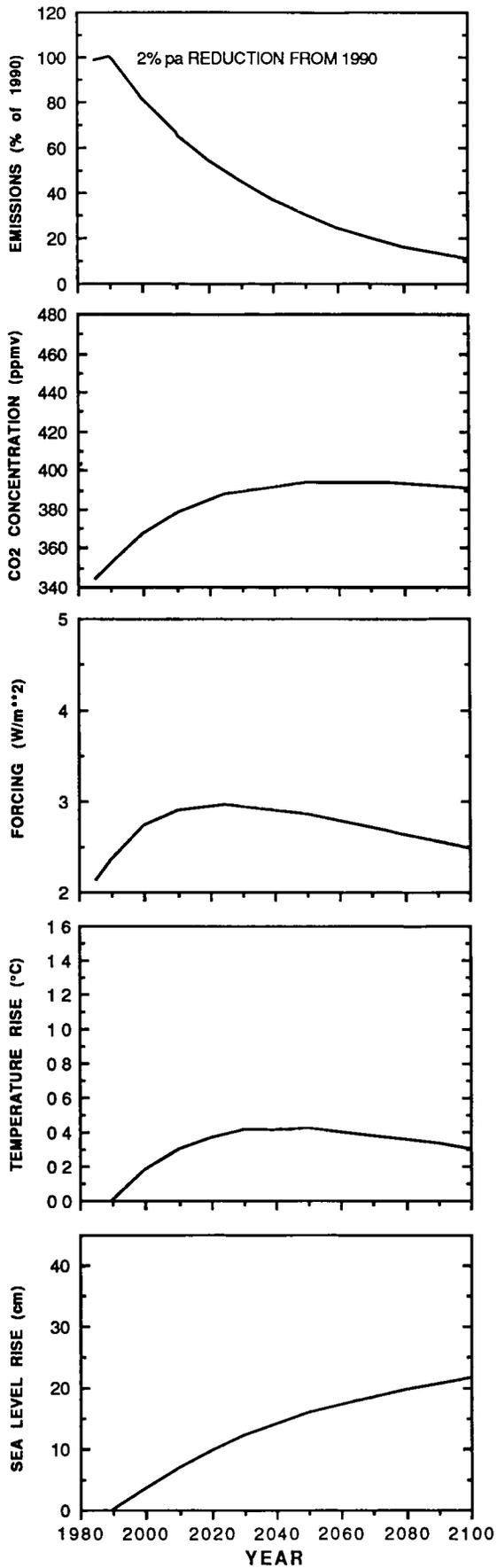


Figure A.17: The complete emissions- sea level rise pathway shown due to decreasing emissions of all man-made greenhouse gases by 2%pa from 1990

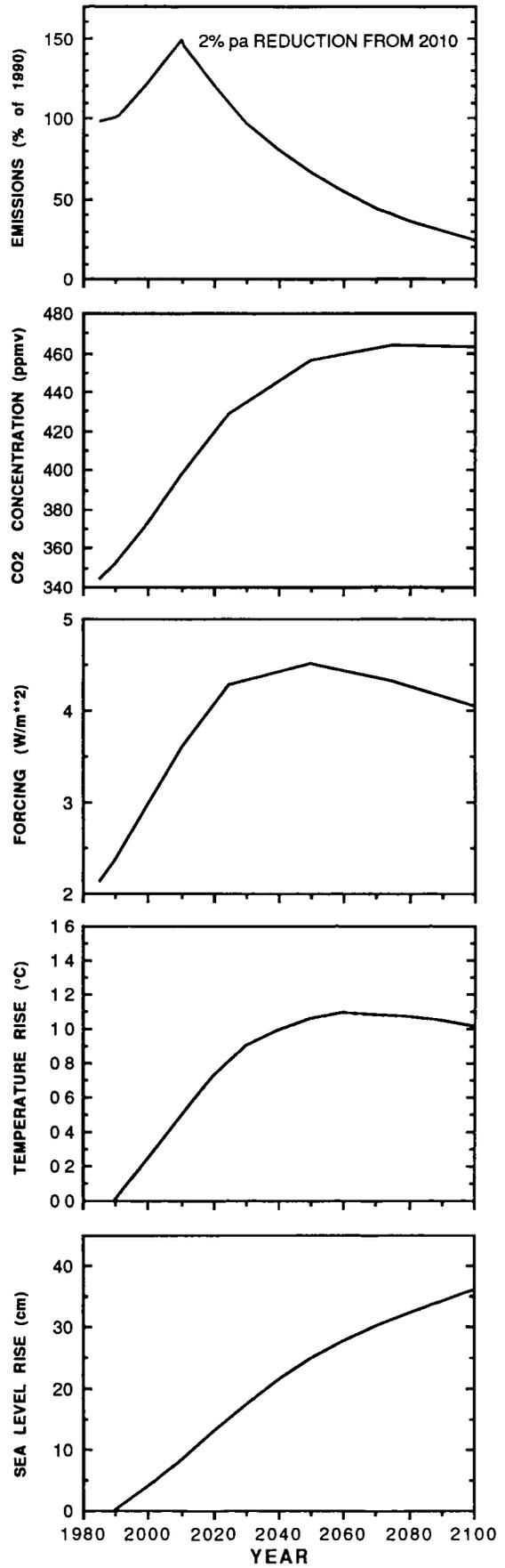


Figure A.18: The complete emissions- sea level rise pathway shown due to increasing emissions of all gases by 2% pa until 2010, followed by decreasing emissions at 2% pa