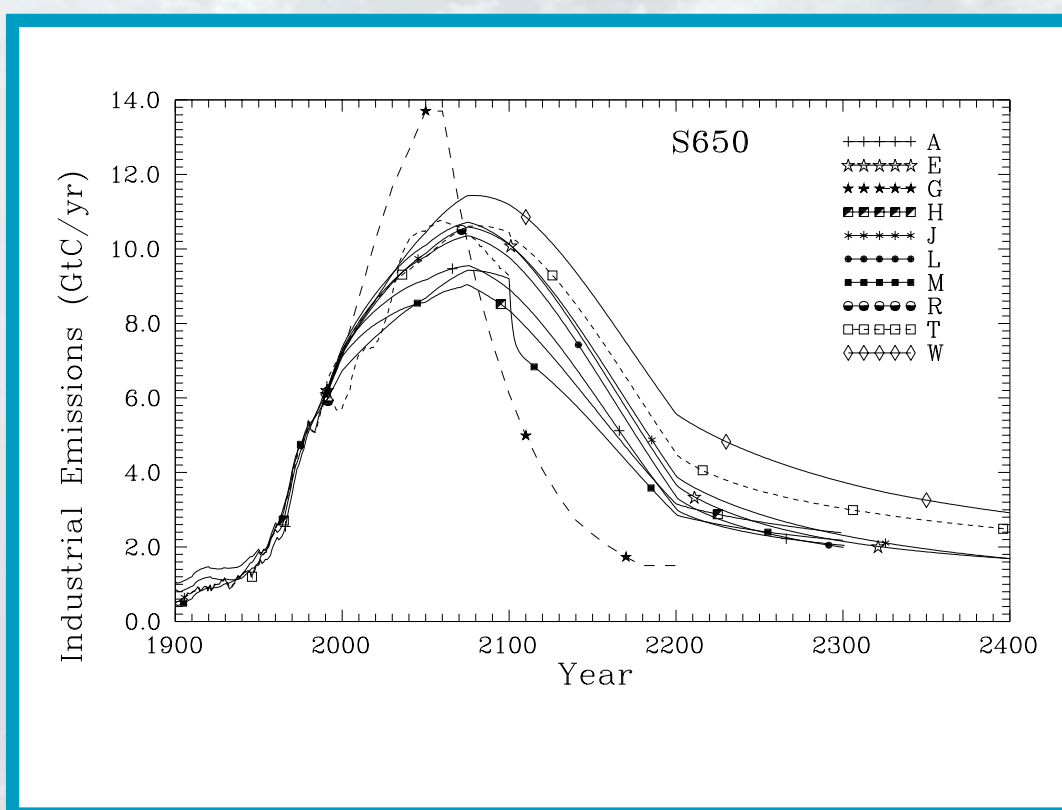


Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses

I.G. Enting, T.M.L. Wigley and M. Heimann



Atmospheric Research

Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses

by I.G. Enting, T.M.L. Wigley and M. Heimann

This report is dedicated to the memory of Ulrich Siegenthaler, 1941–1994, whose work so greatly influenced the modelling presented here.

Cover illustration shows estimates, from ten carbon cycle models, of fossil carbon emissions required to achieve stabilisation of atmospheric CO₂ at 650 ppmv.

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Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses

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Publication History

This report is intended for documentation of the IPCC special report on *Radiative Forcing of Climate Change*.

Release 1. This version was issued over *internet* through anonymous ftp from CSIRO, Aspendale. A limited 'hard-copy' distribution was undertaken from WG1 Technical Support Group, Bracknell, UK. Release 1 was issued solely for the purpose of aiding the review process for the IPCC special report on *Radiative Forcing of Climate Change*. Release 1 was issued 30/3/94, but the cover sheet and page 1 were incorrectly dated 30/3/93. The substantive changes (as opposed to additions) in later versions are that the results for Model Q in 'Release 1' were an earlier 'ocean-only' case, and the ocean differed slightly from the form used for later versions; and Model R denoted the version of IMAGE-2 with CO₂-climate feedback (subsequently denoted R*).

Draft release 2. This was released to IPCC lead authors for comment and also for external review.

Publication This report was produced as part of the CSIRO, DAR Technical Paper series, and also made available, for several months in 1994, as a set of post-script files via internet.¹

Models Z and F₂ were late contributions and so in some places the discussion of these models is less complete than for other models. Information supplied for model T was ambiguous regarding the role of feedbacks.

Electronic edition 2001 The electronic edition was prepared from the original LaTeX files, reformatted from B5 to A4. Minor typographical errors were corrected. Footnotes were added where additional clarification seemed desirable. The incomplete references were left unchanged, but notes were added giving revised publication details.

Data Archiving

In order to assist in the review process of the IPCC reports (IPCC, 1994, 1995) the results of this modelling exercise were made available through anonymous ftp at ftp.dar.csiro.au, on directory ftp/IPCC/results.² These concentrated on results that complied with the specifications in Appendix A. In the longer term, responsibility for handling these data is being transferred to the Carbon Dioxide Information Analysis Center (CDIAC) at Oak Ridge National Laboratory.

The contact details for CDIAC are:
<http://cdiac.esd.orln.gov>³

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¹Footnote to *electronic edition* Still (2001) available at CDIAC.

²Footnote to *electronic edition* No longer available.

³As of Feb 2001, original (1994) details deleted in electronic edition.

Future Emissions and Concentrations of Carbon Dioxide: Key Ocean/Atmosphere/Land Analyses

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Abstract

Various projections of the relation between future CO₂ concentrations and future emissions were undertaken as part of the scientific assessment for Working Group 1 of the Intergovernmental Panel on Climate Change. There were three types of calculation: (i) forward projections, calculating the atmospheric CO₂ concentrations resulting from specified emission scenarios, (ii) inverse calculations determining the emission rates that would be required to achieve stabilisation of CO₂ concentrations via specified pathways and (iii) impulse response function calculations required for determining Global Warming Potentials. The use of a standardised set of conditions allows an intercomparison of models. Sensitivity studies explore other aspects of the uncertainties of such projections. This report documents the specifications, the models that were used and the results that were obtained. Some preliminary interpretations of the results are included.

1. Introduction

This report documents a set of calculations which relate future atmospheric CO₂ concentrations to industrial emissions. These calculations were performed in support of the report on *Radiative Forcing of Climate Change* of the Intergovernmental Panel on Climate Change (IPCC). Calculations were contributed by groups from a number of countries (a list is given as Table 5.1, and summary descriptions of models are given in Appendix C). The specifications for the calculations were prepared by Tom Wigley and Ian Enting who were charged with this duty at the IPCC WG1 Bureau and Ozone Assessment 'Experts' Meeting (Bath, UK, 18–19 February, 1993). These instructions are reproduced in this document as Appendix A.

In assessing these calculations it must be emphasised that they are not 'predictions' of a specific future. We prefer the term 'projections' — calculations of the possible consequences of prescribed courses of action. Similarly, these results do not constitute recommendations on the part of the contributors, the editors or the IPCC. In particular, the pathways to stabilisation are illustrative rather than prescriptive. The calculations are intended to present ranges of options that may be relevant to dealing with the problems arising from greenhouse gas emissions. The results also give an indication of the accuracy with which such calculations can be undertaken at the present time.

One aspect of the calculations that prevents them being regarded as predictions is the neglect of feedbacks between CO₂ and climate. The uncertainties in such feedbacks are too large to justify

defining any standard cases for comparative studies at this time. A small number of calculations with feedbacks were contributed. These are discussed separately in Section 12.

The inputs for the various cases are specified in terms of future values of emissions or concentrations specified as functions of time. It is important to ensure that the definitions are both complete and consistent. These issues are discussed at greater length in Section 2b below.

The main calculations are those concerned with the stabilisation of atmospheric concentrations of CO₂. This emphasis is motivated by the provisions of the UN Framework Convention on Climate Change which has as its objective: *to achieve stabilization of greenhouse gas concentrations . . . at a level that would prevent dangerous anthropogenic interference with the climate system . . . 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.* For the present modelling exercise, we have constructed a set of profiles ¹, defining CO₂ concentrations as functions of time, that lead to constant CO₂ concentrations in the 21st or 22nd centuries.

Previously, projections of future CO₂ had been included in the IPCC reports (IPCC 1990, 1992). The update (IPCC, 1992) included few specific projections of CO₂. However, it did introduce new emission scenarios, IS92a–f, and included assessments of the climatic consequences using the STUGE system (Wigley et al., 1991). This integrated system included a carbon cycle model that was an earlier version of the Model W whose results are reported here.

Our objective has been to present options based on a credible scientific assessment. For this reason, an important part of our report is an analysis of the uncertainties. We have also reviewed the validation and calibration of the models in connection with this analysis.

However, scientific credibility is achieved as a result of critical examination. While the results in this report have been scrutinised during the process of compilation and the overall report has been subject to peer review, the ultimate assessment of its credibility will occur after the results are made freely available to the scientific community.

The modelling presented here is based on a large body of scientific knowledge and experience. While we do not attempt to review the carbon cycle modelling literature, we note a few key general references: Bolin et al. (1981), Bacastow and Bjorkstrom (1981), Broecker and Peng (1982), Emanuel et al. (1985), Sundquist (1985) and Bolin (1986). Other key references are noted in connection with particular topics. ¹²

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¹The preferred IPCC terminology is to reserve the term ‘scenarios’ for those cases that are determined from specific policies.

¹²Footnote to electronic edition Of course up-to-date assessments can be found in the IPCC reports and references there in.

2. Carbon Budget Issues

2a Budget issues

We write the atmospheric carbon budget (in units of Gt C y^{-1}) as:

$$2.123 \frac{d}{dt} C = Q_{\text{foss}}(t) + D_n(t) - S_{\text{ocean}}(t) - S_{\text{fert}}(t) - S_{\text{resid}}(t) \quad (2.1)$$

where:

$C(t)$ is the atmospheric CO₂ concentration (in ppmv relative to dry air),

$Q_{\text{foss}}(t)$ is the 'fossil' emission rate, including both combustion of fossil fuel and CO₂ emissions from cement production. The IPCC (1990, 1992) reports used the term 'industrial' for this component,

$D_n(t)$ is the net carbon flux from land-use change (including delayed effects from past land-use changes),

$S_{\text{ocean}}(t)$ is the net carbon uptake by the oceans,

$S_{\text{fert}}(t)$ is the net flux associated with CO₂-enhanced growth,

$S_{\text{resid}}(t)$ is a residual-sink term, associated with climatic variability and any neglected processes.

The conversion factor, 2.123 GtC/ppmv, is the size of the atmosphere in moles, times the molecular weight of carbon, with the units of gram per unit ratio converted to GtC/ppmv.

There are a number of important points to note about the use of equation (2.1):

1. The budget equation (2.1) describes the perturbation about an assumed pre-industrial steady state. All the terms (except possibly $S_{\text{resid}}(t)$) refer either to anthropogenic forcing ($Q_{\text{foss}}(t)$ and $D_n(t)$) or to the natural response to such forcing ($\frac{d}{dt}C$, $S_{\text{ocean}}(t)$, $S_{\text{fert}}(t)$). These fluxes are net fluxes superimposed on large natural gross fluxes of carbon. In many cases the models will consider the gross fluxes, particularly when calculating isotopic effects. The distinction is well-understood within the field of carbon cycle modelling, but sometimes causes confusion when results are reported.
2. In practice we need to work with time averages of equation (2.1). At the very least we need to average over the seasonal cycle since these intra-annual changes are not included in this perturbation budget. We generally need to average over periods longer than a year in order to define a globally representative rate of change of CO₂. Multi-year averaging can also remove some of the short-term climatic variability that we have assigned to the term $S_{\text{resid}}(t)$.
3. The standard cases defined in the instructions assume that the residual 'missing-sink' term, $S_{\text{resid}}(t)$, is zero.
4. When using this equation in modelling, an initial pre-industrial state needs to be defined. In this connection, Enting (1992) has presented evidence that the fluctuation early in the industrial period shown by the ice-core data is too large to be due to the estimated anthropogenic sources.

2b Issues of definition

As noted in the Introduction, it is essential to ensure that the specifications of the carbon budget are both complete and consistent. Completeness is required both in the mathematical sense of being fully determined and in the physical sense of including all relevant carbon fluxes. However, such completeness must avoid both ‘double-counting’ of any fluxes and mathematical ‘over-specification’ which would generally imply inconsistencies in the description.

The process of mapping fluxes onto compartments with neither double-counting nor under-counting is complicated by the different levels of description that are adopted in different fields of study. In some cases, it is necessary to modify the model structure in order to match the definitions of the prescribed data.

Fossil/Industrial: This is intended to include all anthropogenic contributions to the net atmospheric carbon budget, except for those classified as associated with land-use change. In practice, the contributions are those from fossil fuel usage and cement production. The term ‘industrial’ (as used in IPCC, 1990, 1992) refers to the mode of production and not to the end-use. The term ‘fossil’ is taken to include cement production from fossil carbonate. This report uses ‘industrial’ and ‘fossil’ interchangeably. Estimates for years up to 1950 are based on the work of Keeling (1973) with later values from Rotty (1987) and Andres et al. (1994). The values are tabulated in Appendix A.

Fluxes from land-use change: This term is taken as being the **net** flux associated with present **and past** land use changes. This definition is chosen to match that used by the Woods Hole group (Houghton et al., 1983 and subsequent studies). It includes fluxes associated with deforestation (including decay of forest products), changes in soil carbon, changes associated with varying agricultural regimes, and forest regeneration on previously cleared land. The estimates for the past are from R.A. Houghton (personal communication) and are listed in Appendix A. For the future, we use a modified form of IS92a.

Oceans: This term is taken as the net transfer from the atmosphere to the oceans. There is believed to be a natural cycle in which carbon from the atmosphere is transferred to vegetation, transferred to the oceans via rivers and then returned to the atmosphere through outgassing (Sarmiento and Sundquist, 1992). This cycle can be ignored in the present global modelling. It becomes important when interpreting ocean CO₂ partial pressure data and (to a lesser extent) when interpreting inversions of spatial distributions of CO₂.

‘Fertilisation’: This needs to include all changes in terrestrial carbon that are not associated with land-use change. The key question for the projections presented here is the extent to which such fluxes can be reasonably assumed to grow with long-term increase in CO₂. ENSO-related effects generate short-term variations in the atmospheric carbon budget. A recent study by Dai and Fung (1993) indicates the possible importance of climatic variability on the decadal scale.

Anthropogenic: This is taken as the direct input of carbon to the atmosphere as a result of human activities. We regard this as the sum of the ‘fossil’ and ‘land-use’ components.

We explicitly exclude contributions that arise purely as a result of the increased CO₂ levels. In principle, anthropogenic emissions ought to include any changes in CO₂ fluxes associated with other man-made global change. However, in the present analysis any such fluxes would be included in the 'fertilisation' component in order to balance the budget.

It should also be noted that (2.1) represents an atmospheric carbon budget. Although a fraction of the carbon input enters the atmosphere as compounds other than CO₂, the vast majority of these are quickly oxidised to CO₂. For global averages, on time-scales of years, the atmospheric carbon budget is what determines the rate of increase of CO₂.

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3. Modelling Approaches

3a. The models

Code	Authors	Institution
A	Taylor, Lloyd and Farquhar	Aust. National University
B	Emanuel	Oak Ridge Nat. Lab.
C	Cohen	UN Economic Comm. Europe
E	Enting and Lassey	CSIRO (Aust.) and NIWA (NZ)
F	Friedlingstein	Belgian Inst. for Space Aeronomy
G	Keller and Goldstein	Electric Power Res. Inst.
H	Heimann et al.	Max Planck Inst., Hamburg
J	Joos and Siegenthaler	University of Bern
L	Wuebbles and Jain	Lawrence Livermore Nat. Lab.
M	Moore and Braswell	U. New Hampshire
O	Orr and Monfray	Saclay and CNRS
P	Peng	Oak Ridge Nat. Lab.
Q	Le Quéré, Sarmiento and Pacala	Princeton
R	Alcamo and Krol	RIVM, Netherlands
T	Harvey	U. Toronto, Canada
V	Viecelli	Lawrence Livermore Nat. Lab.
W	Wigley	OIES, UCAR, Boulder, Colorado
Z	Zakharova and Selyakov	State Hydrol. Inst., St. Petersburg

Table 3.1. Index of modelling groups.

The invitation to participate in the modelling exercise drew responses from many groups, each using a different model. For convenience of identification, each model has been given an identifying letter (generally having a mnemonic association with author or institution). These are listed in Table 3.1. Appendix C gives a summary description of each model.

3b. General Issues

The ocean models used in the calculations presented here span a range of forms from response function descriptions to general circulation models. Enting (1987) has described this range in terms of the ‘modelling spectrum’ concept of Karplus (1977) with models ranging from ‘black-box’ (inductively derived) to ‘white box’ (deduced from basic principles). The general issue for all levels of modelling is whether the model parameters can reasonably be regarded as being the same in the future as at present.

One way of grouping modelling approaches is:

Extrapolation: This is based on extrapolating the trends in CO₂. This is generally done in statistical terms (e.g. Mannermaa and Karras, 1989). This approach has no capability of relating concentrations to emissions. It makes an implicit assumption about the continuation of current patterns of emissions.

Total response function description: The CO₂ increase is related to emissions through a response function formalism. This approach was used for the present exercise by Cohen (Model C). He derived his response function empirically by statistical fits to historical data. It would, however, be possible to derive this type of total response function from mechanistic models.

Combination of response functions and parameterised models: This description includes numerous possibilities. This approach was used for the present exercise by Wigley (Model W) and Harvey (Model T). They used response function representations of the ocean and parameterised models of the terrestrial systems. The ocean response functions were derived from mechanistic ocean models. Model V uses an empirical fit to an effective lifetime for the combined excess carbon content of the atmosphere and ocean surface.

Parameterised models: These are models with 'lumped' descriptions of actual processes. The way in which they differ from parameterisations in terms of response functions is that the same parameterisation is assumed to apply in more than one situation, making validation and/or calibration possible. For carbon cycle studies, the general assumption is that such parameterised models are adequate for defining relations between the behaviours of the different carbon isotopes, thus allowing the use of isotopic data in model calibration. All of the terrestrial components used in the present studies have been parameterised to a significant degree. The majority of the ocean models were highly parameterised (B, E, G, J, L, M, P, R, Z).

Mechanistic models: These derive the behaviour deductively from fundamental physical and chemical principles. The various ocean general circulation models (Models H, O, Q) fall into this class, although even here some empirical parameterisation is involved.

Other important general issues in the modelling are:

The role of statistics: In terms of the model spectrum described above, statistical modelling is generally associated with the highly parameterised 'black-box' end of the model spectrum. In particular, the main applications of statistical analysis to problems of CO₂ have been the 'extrapolation' type analyses described above as having little explanatory power. However, the association of statistical analysis with the black-box end of the spectrum is not essential. Some applications of statistical analysis have been in model calibrations and uncertainty analysis (see also Section 11 below). Enting and Pearman (1987) used a least squares fitting procedure for calibration and uncertainty analysis. A more sophisticated approach is described by Gardner and Trabalka (1985).

One way of integrating statistical analysis into the modelling is through a state-space representation as suggested by Enting (1989b). In that work it was pointed out that the representation of response functions as sums of exponentials led to a simple recursive expression for the CO₂ concentration (as subsequently used in a deterministic context by Wigley, 1991) and that this mapped directly onto a state-space representation of an auto-regressive model. The particular application considered by Enting (1989b) was a Kalman filtering analysis of ice-core data, but the potential applications of such state-space representations are far wider than this.

Forward vs. inverse modelling: An important technical distinction in modelling is between forward modelling and inverse modelling. In the present context forward modelling involves using a specified emission profile, $Q(t)$, to calculate the concentration, $C(t)$, and inverse modelling is the process of deducing the emission profile, $Q(t)$, given the concentrations, $C(t)$. Different implementations of carbon cycle models differ in how readily inverse calculations can be undertaken. Some aspects of inverse modelling are presented in note A.6.D below. More detailed discussions are given by Enting and Mansbridge (1987) and Wigley (1991, 1993).

Three of the ways in which inverse calculations can be undertaken are:

- directly with a model that can enforce mass-balance at each time step, (i.e., an ‘inverse model’);
- iteratively with a forward model, possibly by applying an approximate inverse model to the discrepancies between calculated and prescribed concentrations at each iteration;
- ‘off-line’ using a response function in some way, e.g. the inverse model of Wigley (1991) or an implementation of the formalism of Enting and Mansbridge (1987).

Table 5.1 indicates the way in which each model was initialised.

3c. The conceptual framework

The instructions contained in Appendix A have imposed a particular conceptual framework on the calculations. Specifically, the atmospheric carbon concentration is being treated as the result of two anthropogenic forcing terms subject to the effects of two natural dissipative responses.

The anthropogenic forcing terms are the fossil carbon release, Q_{foss} , and the **net** carbon flux from land-use-change, D_n . Section 9 exploits this representation by expressing it in a response function form (valid for the linear regime) as

$$N_a(t) = 2.123[C(t) - C_0] = \int_0^\infty G_a(\tau) Q(t - \tau) d\tau \quad (3.1)$$

In this representation, $Q(t)$ is the total anthropogenic forcing:

$$Q(t) = Q_{\text{foss}}(t) + D_n(t) \quad (3.2)$$

and the atmospheric response function G_a represents the combined ‘natural’ response: oceanic and biotic. (The response function G_a can be constructed from the separate responses of the oceanic and biotic components as described in Section 9c, below.)

The reasons for adopting this approach are;

- It is consistent with the majority of models used in carbon cycle studies;
- It is consistent with the definitions of the data sets used, particularly the specification of net fluxes from land-use-change by Houghton et al. (1983; and later updates);
- It is an appropriate framework for the calculations in which we are interested.

The compatibility between models, data sets and requirements has, of course, evolved through experience. Nevertheless, the framework that we have adopted is not the only way of addressing the problems of modelling the carbon cycle. The main scope for difference lies in the terrestrial components; indeed a number of modellers have had to make minor changes to their standard approach in order to fit the specified framework. One model which has adopted a more general terrestrial modelling technique is Model B. The differences are sufficiently great to preclude direct comparison with the other model calculations presented here. Further details are given in Section 12c.

The inversion of (3.1) implies that $Q(t)$ is calculated from $C(t)$. The instructions in Appendix A requested that modellers report not the total anthropogenic emissions, $Q(t)$, but rather the fossil component, $Q_{\text{foss}}(t)$, obtained by assuming a specified land-use component $D_n(t)$. There are, however, two important reasons why reporting $Q(t)$ is preferable:

- The objectives of the Framework Convention on Climate Change are phrased in terms of concentrations, and these do not distinguish between the classes of emission.
- The total emissions are (to a first approximation) dependent only on the prescribed CO_2 histories, while, for a given pathway to stabilisation, the fossil component depends on what scenario is chosen for future land-use fluxes. When reporting total anthropogenic emissions, that fact that we have considered only one scenario for the land-use flux is largely irrelevant.

For these reasons, some of the key results have been converted back to total anthropogenic fluxes, and it is these that are reported in IPCC (1994).

3d. Ocean models

One of the ocean models used by several groups was the ‘box-diffusion model’ of Oeschger et al. (1975). This is a highly parameterised model with a single surface mixed layer and a deep-ocean reservoir which is treated as uniform horizontally and in which transport in the vertical

is modelled as eddy-diffusion with a single ‘eddy-diffusion coefficient’, K , parameterising the transport.

The box-diffusion model provides an example of the range of uncertainty in calibrating parameterised models. Table 3.2 lists the range of estimates of the diffusion parameter. The ^3H calibration by Broecker et al. (1980) was used in some of the CO_2 projections reported in the IPCC (1990) assessment (see Enting, 1991).

Calibration	K	Reference
^{14}C (natural)	3987	Oeschger et al. (1975)
^3H (bomb)	5364	Broecker et al. (1980)
^{14}C (bomb)	7685	Siegenthaler (1983); Model B
Various ^{14}C	6245	Enting and Lassey (1993)
^{14}C (natural)	4350	Siegenthaler and Oeschger (1987); Model A
Various ^{14}C	5859	Model E
	7573	Model P

Table 3.2. Calibrations of the box-diffusion model of ocean carbon uptake. K is the eddy-diffusion coefficient in m^2y^{-1} .

A more complicated model is the HILDA model. This incorporates a two-region description of the ocean, an advective circulation and a depth-dependent eddy-diffusion coefficient. Although these features had been incorporated into previous ocean models (both separately and in combination) the HILDA model has been widely studied (Siegenthaler and Joos, 1992) and it is used as the ocean component of several of the calculations reported here.

The most complicated models are those based on ‘ocean general circulation models’ (OGCMs), represented in this study by Models H, O and Q. These use the ocean transport calculated from the equations of ocean dynamics. The most common mode of operation is to run an OGCM to calculate ocean transport (e.g. as velocities) and to store these results for use in calculations of the transport of carbon and other ocean tracers without having to repeat the dynamical calculations.

In principle, such an approach could remove the need for model parameterisation but in practice the representation of the sub-grid-scale processes in OGCMs needs to be tuned. Nevertheless, transport modelling based on OGCMs has the advantage of transport fields that are consistent with the dynamical equations and generally consistent with observations of temperature, salinity and usually additional tracers.

3e. Terrestrial carbon models

Modelling the terrestrial components of the carbon cycle presents an extremely difficult challenge because of the scarcity of universally applicable principles. The most common way of

modelling terrestrial carbon transfers is to use discrete compartments. Typically, these represent physical divisions such as leaves, branches, litter, roots and soil carbon. The most important characteristics of these compartments are the turn-over times or ‘reservoir lifetimes’ and the initial carbon contents. In the context of the present calculations, these turn-over times are important because they affect the amount of carbon storage that results from CO₂-enhanced growth. The reservoir turnover times also affect the response to perturbations in the isotopic composition of atmospheric CO₂. Thus, isotopic data provide some validation of reservoir turn-over times. In particular, ¹⁴C data can be used to estimate mean ages for soil carbon.

The terrestrial models used by the various groups represented here differ somewhat in the number of physiological compartments used (generally from two to six). However, the main difference is in the degree of disaggregation into regions and ecosystems, i.e., the question of whether the physiological compartments are used as global averages or treated separately for a set of classes based on division by ecosystem type and/or region.

The general form of the models is that, for each class, there is a Net Primary Production (NPP) that transfers carbon from the atmosphere into plants. Transfers between compartments and back to the atmosphere generally depend on the carbon content of the compartment, typically being described by a first-order decay process. (In some of the more sophisticated models, the rate constants can depend on external variables such as temperature). The NPP can also depend on variables such as temperature, nutrient levels, water supply, etc. The most important dependence for our studies is the possible dependence of NPP on atmospheric CO₂ concentration since this will ultimately limit the ability of terrestrial systems to store additional carbon.

Appendix A suggests three forms of dependence:

Linear

$$\text{NPP} = \text{NPP}(C_0)[1 + \beta_1[C(t) - C(0)]/C(0)] \quad (3.3a)$$

Logarithmic

$$\text{NPP} = \text{NPP}(C_0)[1 + \beta_2 \ln[C(t)/C(0)]] \quad (3.3b)$$

and Hyperbolic

$$\text{NPP} = \text{NPP}(C_0) \left[1 + \frac{\beta_3[C(t) - C(0)][C(0) + X]}{C(0)[C(t) + X]} \right] \quad (3.3c)$$

where $C(0)$ is an initial reference concentration and the β_j are non-dimensional values of the sensitivity of NPP to CO₂. In (3.3c) X is an additional parameter that (with β_3) determines the maximum NPP.

The modelling framework embodied in equation (3.1) implies that the carbon flux from land-use change should be specified in terms of a net flux. Enting and Lassey (1993) pointed out that the use of first-order transfer processes would mean that any perturbation applied to such a reservoir would lead to a relaxation back to the equilibrium carbon content once the perturbation ceased. In other words there would be a ‘regrowth’ in response to carbon loss and so the perturbation would not correspond to the net carbon flux. A correction term (expressed by Enting and Lassey as a simple integral when only one reservoir was involved) is required to convert specified net

fluxes to the gross fluxes required in models in which the reservoir size is subject to a first-order response.

A more comprehensive way of addressing the question is to model the regrowth in an internally consistent manner and apply perturbations in terms of the processes of land-use change. In other words, the type of modelling used by Houghton et al. (1983) to produce estimates of D_n could be incorporated into the carbon cycle model rather than being used to define D_n as an external forcing. This type of approach was used in Model B. The difference in approach makes it difficult to compare these results to cases that use the standard description. Model B is discussed in more detail in Section 12c.

3e. Issues for future work

Since the instructions in Appendix A were drawn up, work on the carbon cycle has continued and some of the issues have become clearer. A number of activities have contributed to this. Firstly there is, of course, the experience of having a number of groups perform the set of calculations. This exercise has revealed issues that were less obvious before we commenced. Secondly, there have been a number of scientific meetings addressing the issues of concern in making projections of CO₂. (e.g. The Global Change Institute on the Global Carbon Cycle, Snowmass Village, July 1993, and The Fourth International CO₂ Conference, Carqueiranne, September 1993).

In general, such discussions have left us with clearer statements of the problems rather than new solutions. Among the key issues are:

- Can we do better than assume a 'neutral' biosphere? (i.e., unchanging biomass). The assumption of no future biotic change was implicit in many of the calculations produced for the IPCC (1990) report.
- Is a declining 'land-use' source (e.g. IS92a, implying a managed biosphere) an appropriate assumption? In the present studies, it has been adopted in the stabilisation scenarios/profiles, on the basis that any commitment to reduce CO₂ emissions is likely to be implemented by reductions in both industrial and biotic releases.
- Since the 'land-use' component is relatively small, does the precise form matter particularly?
- Are there any global integrals or constraints for terrestrial ecosystems that apply in a way analogous to the ¹⁴C constraint on oceanic CO₂ uptake? For example, are there physiological constraints that can be translated into maximum carbon loadings for particular ecosystems?
- Is terrestrial modelling preferable to scenarios for D_n ?
- Is a more integrated description (sometimes called 'layered modelling') appropriate, e.g. with both industrial and land-use fluxes modelled in terms of specific societal changes?

Another issue that has arisen from work since the instructions were drawn up concerns the atmospheric carbon budget. The instructions specify a mean 1980s' growth rate of 1.59 ppmv y^{-1} . Detailed analysis by Tans and co-workers (personal communication) suggests a global mean growth rate of 1.53 ppmv y^{-1} . This estimate was based on the use of a two-dimensional model analysis of data from the NOAA CMDL flask sampling network. A more significant revision to the budget is the IPCC (1994) preferred estimate of 1.1 Gt C y^{-1} rather than 1.6 Gt C y^{-1} for the net flux due to land-use change.

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4. Strategies for Achieving Carbon Balance

The atmospheric carbon balance, with the assumption that CO₂-fertilisation accounts for all the ‘missing sink’, is expressed as:

$$2.123 \frac{d}{dt} C(t) = Q_{\text{foss}}(t) + D_n(t) - S_{\text{ocean}}(t) - S_{\text{fert}}(t) \quad (4.1)$$

This provides an essential constraint on the modelling. In general terms, the specifications in Appendix A invoke two principles:

1. The terms in the current (i.e., 1980s’ mean) modelled carbon budget as expressed by equation (4.1) should be consistent with observations.
2. There should be continuity in processes from the past to the future: the future balance should be achieved using the same processes as for the past.

Two of the ways in which these requirements translate into procedures for initialising the models for calculations beyond 1990 are:

The standard forward initialisation: Use $Q_{\text{foss}}(t)$, $D_n(t)$ exactly as specified, with $S_{\text{ocean}}(t)$ calculated (possibly using a ¹⁴C calibration) and $S_{\text{fert}}(t)$ calculated. The parameterisation of S_{fert} is tuned to give the best possible agreement with the observed record of $C(t)$. The precise details of how this is done are left open.

The standard inverse initialisation: Use specified $Q_{\text{foss}}(t)$ and calculated $S_{\text{fert}}(t)$ and $S_{\text{ocean}}(t)$ and track the prescribed $C(t)$ in order to deduce $D_n(t)$. The model parameters are to be tuned to give $\bar{D}_n = 1.6$ GtC/yr averaged over the 1980s.

Post-1990: The fluxes S_{ocean} and S_{fert} are to be calculated using the same parameters as in the initialisation phase. The land-use flux D_n is prescribed. This leaves the model integration defining a relation between $Q_{\text{foss}}(t)$ and $C(t)$, either of which can be used to determine the other. Calculations of both types are requested in the instructions.

The prescribed CO₂ concentration for the period 1 January 1980 to 31 December 1989 shows an increase of 15.9 ppmv, an average rate of increase of 3.38 GtC/yr. For the same period our standard cases had average sources of $\bar{Q}_{\text{foss}} = 5.45$ GtC/yr and $\bar{D}_n = 1.58$ GtC/yr. In terms of the atmospheric budget shown in equation (4.1), this constrains the sum of oceanic and fertilisation fluxes to be $S_{\text{ocean}} + \bar{S}_{\text{fert}} = 3.65$ or more generally $S_{\text{ocean}} + \bar{S}_{\text{fert}} = 2.07 + \bar{D}_n$. This is shown diagrammatically in Figure 4.1. It is possible to take combinations of the oceanic and terrestrial fluxes, whether computed by full models or partial models, and combine them in pairs subject to the balance constraint.

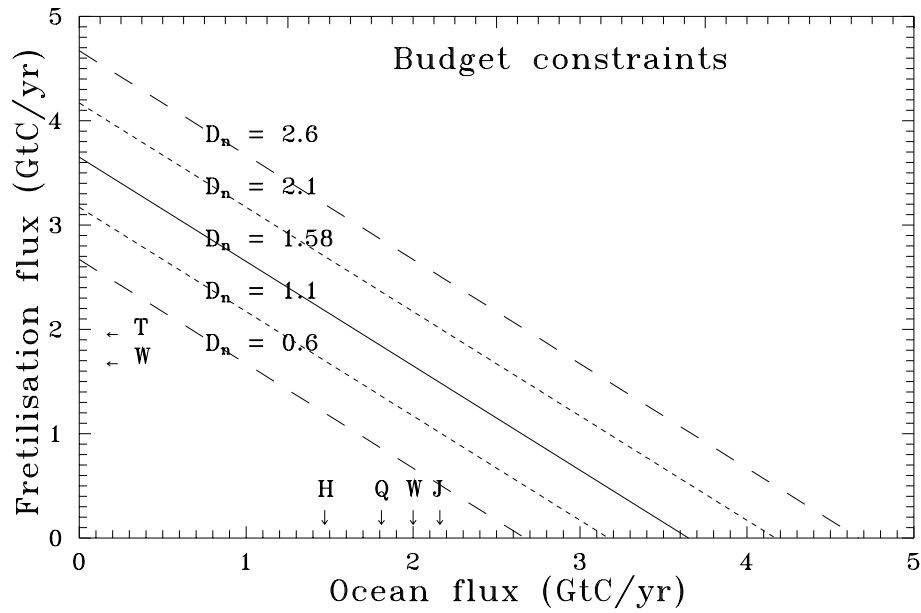


Figure 4.1. Relation between components of the atmospheric carbon budget averaged over 1980–89. The lines for various mean 'land-use' fluxes specify the combinations of ocean flux and fertilisation flux that are compatible with a balanced atmospheric budget. Labelled points along the axes show fluxes calculated for some of the models. Within the specifications of Appendix A, the 'fertilisation' and 'ocean' components of different models can be combined, subject to implying an acceptable 'land-use' term.

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5. Summary of Models

5.1 Descriptions

Table 5.1 summarises the main characteristics of the various models listed in Table 3.1. They are grouped according to the representation of the oceans, comprising one statistical representation of all sink processes (Model C); one with an empirical ‘lifetime’ for the combined excess carbon in the atmosphere and ocean surface (Model V); one terrestrial-only Model (F); a two-box ocean Model (Z); three with response function representations (F_2 , T and W); four versions of the box-diffusion model introduced by Oeschger et al. (1975) (A, B, E, P); three implementations of the HILDA model (G, J, L); one implementation of the 12-box ocean model of Bolin et al. (1983) (Model M); an alternative 12-box advective-diffusive model (R); and three ocean general circulation models (H, O and Q). These types of model are described in Section 3b, above.

The representations of the terrestrial components are more diverse.

Model	Ocean	Land	Initialisation	Fertilisation
F	None			Logarithmic
C	(with land)	(with ocean)		
V	lifetime	None		
Z	2-box	None	Inverse	
F_2	Response function	$(5^\circ \times 5^\circ) \times 9$		Hyperbolic
T	Response function	6-box	Inverse	Logarithmic
W	Response function	4-box	Inverse	Hyperbolic
A_1	BDM	ANU-BACE	Inverse	Mechanistic
A_2	BDM	ANU-BACE	Forward	Mechanistic
B	BDM			
E	BDM	2-box	Forward	Hyperbolic
P	BDM	None		-
G	Hilda	6×6	Forward	
J	Hilda	4-box	Inverse	Logarithmic
L	Hilda	6-box	Inverse	Logarithmic
M	12-box			
R, R*	12-box	Image 2.0		
H	HAMOCC-3	OBM3m	Inverse	\approx Hyper.
O	LODYC GCM	None	Inverse	None
Q	GCM		Inverse	

Table 5.1. Characteristics of models. A_1 and A_2 denote alternative initialisations. R* and R denote IMAGE 2.0 with and without CO₂-climate feedback. The $n \times m$ notation for the terrestrial component is number of ecosystem/region classes \times number of physiological reservoirs.

The models differ in the extent to which they have complied with the specifications in Appendix A. We can group them as:

Full models with inverse initialisation: Those models following essentially the procedure of Section 4 were J, L, T and W. Models A₁ and H used a modified inverse approach, performing forward runs to tune the fertilisation to give a budget that balanced over the period 1960–1990, and then running the model in inverse mode over both past and future to deduce industrial emissions. Model Q was also initialised by deducing industrial emissions.

Full models with standard forward initialisation: These followed essentially the forward procedure of Section 4. The models were A₂, E.

Ocean-only models: As noted above, these can provide useful information for those cases prescribed as inverse calculations. The models were O, P, V, Z.

Terrestrial-only models: Similarly, these can be useful for the inverse cases. The only case here is Model F.

Models with climatic feedbacks: The standard specifications requested that climatic feedbacks NOT be included. We discuss runs with climate feedbacks in Section 12b. For the moment we note that these cases will not be directly comparable with the no-feedback cases. Runs with climate feedbacks are either excluded from comparisons or are flagged specially. The models were R*, T.

Models failing to fit the prescribed stabilisation curves adequately: These were Models G, V.

Others: The statistical representation (Model C) failed to comply with the basic process description. Perhaps a more important failing is that it worked in terms of responses for total CO₂ rather than the perturbation.

In contrast, Model B is not directly comparable with the other models because its representation is more detailed than envisaged in the specified scenarios so that it is not fully compatible with the specifications. In particular, it used an inverse initialisation to deduce an unidentified sink that was continued into the future.

To summarise, the models that can be directly compared for the stabilisation calculations are A₁, E, H, J, L, M, Q, R and W. Models R* and T¹ differ by including climatic feedbacks; they are not directly comparable but are included in various tabulations of results for completeness. For forward calculations this set of nine models can be augmented by Model G; in the inverse calculations, model G used an alternative CO₂ profile. This is discussed further in Appendix F. The ocean-only models (O, P, V, Z) provide additional comparisons of oceanic uptake in the stabilisation cases (although V had a poor fit to the specified concentration profiles), Model F provides a similar comparison of biotic uptake, and Model B provides an additional comparison of the effects of different choices regarding the terrestrial component.

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¹Information provided about feedbacks in Model T was ambiguous.

6. Initialisation

6a Budgets

A key specification in the modelling exercise was the requirement for a balanced atmospheric carbon budget consistent with observations. Table 6.1 summarises the way in which various models achieved this balance over the period 1980–89. Figures 6.1 and 6.2 show more detail, giving the time history of calculated concentrations (for forward initialisations) and calculated emissions (for inverse initialisations) respectively.

	Initialisation	Fossil	Ocean	Fertil	Land-use	Biota	$\frac{dC}{dt}$
A ₁	Inverse*	5.65	2.03	1.85	1.56	0.29	1.59
F ₂	Inverse	5.50	1.99			1.72	1.59
H	Inverse*	5.63	1.47			0.76	1.59
J	Inverse	5.45	2.16			-0.08	1.59
L	Inverse	5.45	2.14		1.60	0.12	
M	Inverse	5.58	1.72			0.48	1.59
Q	Inverse*		1.81				
T	Inverse	5.41	1.79	1.95	1.68		1.59
W	Inverse	5.45	2.00	1.67	1.60	0.07	1.59
A ₂	Forward	5.49	2.00	1.87	1.29	0.58	1.39
E	Forward	5.48	2.10			0.27	1.50
O	Ocean-only		2.10				

Table 6.1. Mean budgets (or budget components) for 1980–89. Fluxes are in GtC/yr and are sinks except for the fossil and land-use terms. The ‘biota’ term is the annual mean increase in biomass, equal to fertilisation minus land-use. The mean atmospheric increase is in ppmv/yr. The * denotes a modified inverse initialisation.

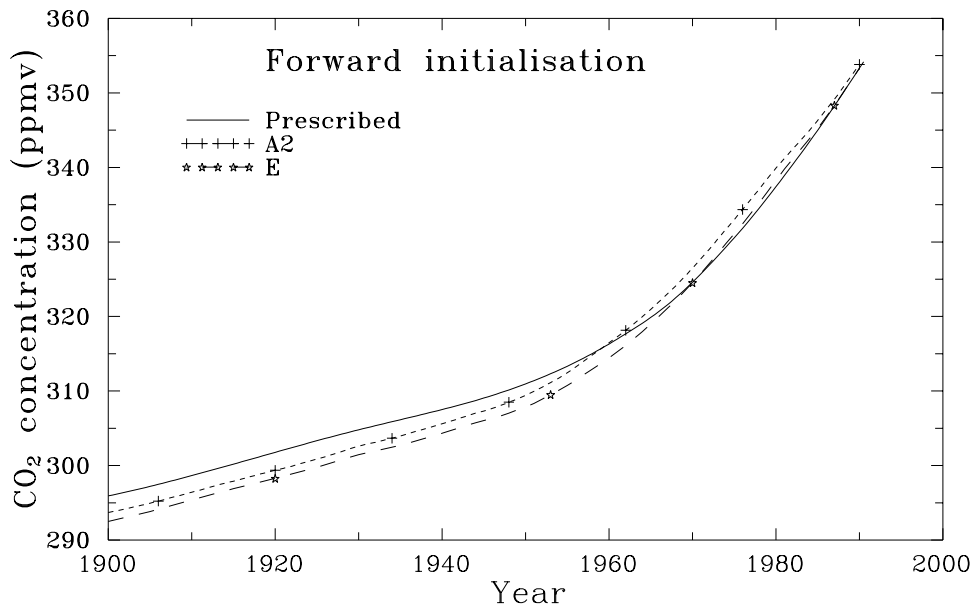


Figure 6.1. Calculated concentrations for models with forward initialisation.

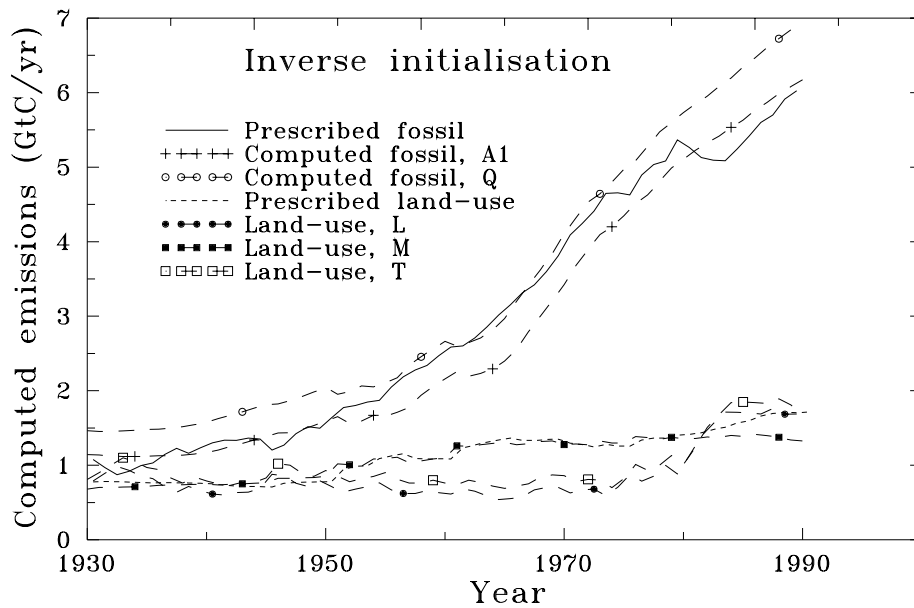


Figure 6.2. Calculated emissions for models with inverse initialisations, compared to prescribed functions. There are two groups, depending on whether the fossil or the land-use component was deduced in the inversion.

6b Validation

The validation of carbon cycle models is a key issue in establishing the credibility of the projections that can be made for future concentrations. The main scope for validation is for the ocean component, for the following reasons:

- The chemical relations between ocean carbon content and CO₂ partial pressure are well-known from measurement.
- The atmosphere and the ocean surface mixed layer are close to equilibrium; uncertainties in the air-sea gas exchange coefficient have little impact on carbon cycle model projections, even though they are critical in the interpretation of ocean P_{CO₂} data.
- The rate-limiting process for oceanic uptake of CO₂ is the rate of physical mixing of water masses. This will have the same impact on all oceanic constituents and makes it possible to use other passive tracers to validate ocean carbon models.
- The biotic processes affecting ocean carbon do not affect the rate of uptake of anthropogenic CO₂ unless these biotic processes actually change.

The radioactive isotope ¹⁴C plays a key role in the calibration and validation of ocean carbon models. Two aspects of the ¹⁴C distribution are important: the natural distribution, in which different ¹⁴C levels reflect the effect of radioactive decay (half-life 5730 years) and the excess ¹⁴C from nuclear testing when atmospheric ¹⁴C levels almost doubled in the early 1960s. Extensive data sets of oceanic ¹⁴C were obtained in the GEOSECS program (circa 1973), the TTO program (1981–3) (Brewer et al., 1985) and are part of the on-going WOCE program.

¹⁴C data play a small role in validating models of terrestrial carbon. As noted above, ¹⁴C data have been used to estimate turn-over times for soil carbon. One important use of terrestrial ¹⁴C data is as a proxy for atmospheric ¹⁴C in determining the Suess effect (i.e., the decline in the proportion of atmospheric ¹⁴C due to dilution of the atmospheric reservoir by CO₂ derived from fossil sources in which all the ¹⁴C has decayed).

The use of bomb-¹⁴C poses some difficulties because the sources are poorly known, due to military secrecy. The usual way of using bomb-¹⁴C in carbon cycle models is to specify the atmospheric ¹⁴C levels from observations. For the present exercise, specified ¹⁴C levels were provided. These are plotted in Figure B.5. To make best use of such data, the ¹⁴C calculation should be performed in ‘inverse’ mode, deducing the sources to ensure that the calculated source went to zero after the cessation of atmospheric testing. Alternatively, the calculation could be performed in inverse mode during the period of testing and ‘forward’ mode thereafter, to check that the decline in atmospheric ¹⁴C levels matched observations. Enting and Lassey (1993) addressed this problem by performing the ¹⁴C calculations in ‘forward’ mode throughout, with a ‘bomb-¹⁴C production factor’ to take account of source uncertainty and tuned to match observations. Some aspects of the ¹⁴C calibration issue are analysed by Enting (1990).

In analysing oceanic ^{14}C data, it has become common to use the penetration depth z_{pen} as a measure for comparing models. The penetration depth is defined as the ratio of the volume-integrated bomb- ^{14}C inventory to the area-averaged surface bomb- ^{14}C levels. (Each of the factors requires an estimate of pre-bomb levels in order to calculate the excess from current observations.) The penetration depth gives a measure of transport out of the surface mixed layer. This is the quantity of most interest for the uptake of anthropogenic CO_2 . In contrast, the mixed-layer ^{14}C level is strongly influenced by the air-sea gas exchange rate, a quantity that is somewhat uncertain but which has little influence on long-term rates of uptake of CO_2 .

A small number of modelling groups submitted specific results for ^{14}C . Other groups referred to their published model descriptions in which results for ^{14}C (and in some cases other tracers) were included.

The summary of ^{14}C validation data relevant to the present calculations is:

Not applicable The ocean ^{14}C data can not be applied to the models that do not resolve the ocean: Model C which parameterises atmospheric response, Model F which is biosphere-only, Models T, V and W which represent the ocean in terms of response functions, and Model Z which has too little resolution. The validation of response function representations derived from other models can be achieved by reference to the original model, but this linkage is lost if there is subsequent ‘tuning’ of the response function. A closer linkage between CO_2 and ^{14}C could be achieved in terms of response functions describing perturbations to the mixed layer (as used in other contexts by Enting, 1990, and Heimann and Maier-Reimer, 1994).

Contributed The models for which ^{14}C data were calculated were E, J, L, O, Q, with Table 6.2 giving a summary of what was provided.

Published In addition Models H, J, L, Q referred to work, published or in preparation, describing aspects of the model calibration.

Table 6.3 compares some of the key results.

	t	E	J	L	O	Q
Mixed layer	all	Y	Y	Y	Y	Y
Inventory	all	-	Y	-	Y	Y
Mixed layer	1974	Y	Y	Y	Y	Y
Inventory	1974	Y	Y	-	Y	Y
z_{pen}	1974	Y	Y	-	Y	Y

Table 6.2. ^{14}C calibration data. ‘Y’ denotes ^{14}C data contributed. For the box-diffusion models (A,B,E,P) various analyses of ^{14}C have been published.

	Total 1950	Mixed 1950	Total 1973	Mixed 1973	Δ Total 50 – 73	Δ Mixed 50 – 73	z_{pen}	S_{ocean} 1980
Obs.						157		—
E		−60.5		101.9		162		2.00
H					9.27	189	320	1.32
J	0.78	−59.1	8.62	93.6	7.84	155		1.94
L					8.4		310	1.95
O					7.18	159		1.89
Q	525.2	−52.1	533.6	145	8.42	197	304	2.39

Table 6.3. Ocean ^{14}C levels. The mixed layer values are in ‰. Depth-integrated totals are in 10^9 atoms cm^{-2} . The penetration depth z_{pen} is in metres. The observations are from the analysis by Broecker et al. (1985).

One aspect of the importance of the ^{14}C calibration is indicated by Model A. As indicated in Table 3.2, this uses the calibration from Siegenthaler and Oeschger (1987) based on natural ^{14}C . Siegenthaler and Oeschger suggested that this should give a lower bound on the oceanic carbon uptake. Calibrations based on bomb- ^{14}C give higher eddy diffusion coefficients (see Table 3.2) and thus greater uptake (see Table 8.3).

A recent study by Hesshaimer et al. (1994) (see also Joos, 1994) has re-analysed the ^{14}C records using an approach similar to the ‘inverse’ followed by ‘forward’ procedure described above. They have queried the conventional analysis of the ^{14}C budget. This result requires further analysis.

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7. Summary of Results for Forward Calculations

Model	IS92c	IS92a	IS92e	DEC0%	DEC1%	DEC2%
A ₂		518.6		464.2	442.0	426.2
B ₁		520.9				
B ₂		522.8				
B ₃		512.6				
G		509.8		458.3	437.1	422.0
	—	—	—	—	—	—
E	437.7	494.1	541.6	438.9	416.5	400.8
J	442.1	498.7	546.0	443.4	421.0	405.4
L	441.0	497.9	545.5	443.7	421.4	405.8
W	437.4	497.4	547.4	438.6	414.3	397.1
Z	420.9	480.2	530.0	421.7	397.9	—
R*	432.1	495.1	548.1			
T	438.1	494.9				

Table 7.1. Projections of CO₂ for 2050 for forward calculations. Model Z is ‘ocean-only’. The two ‘feedback’ cases, R* and T, are included for completeness in the lower section.

Model	IS92c	IS92a	IS92e	DEC0%	DEC1%	DEC2%
A ₂		731.3		537.4	467.5	432.1
B ₁		734.0				
B ₂		731.2				
B ₃		728.4				
G		719.8		534.0	464.1	428.2
	—	—	—	—	—	—
E	468.7	683.9	913.1	492.7	425.4	392.9
J	474.2	687.7	910.4	498.2	430.3	397.2
L	473.0	687.0	908.3	502.6	434.2	402.7
W	456.4	676.5	909.2	481.4	411.4	377.3
Z	420.6	628.7	856.9	444.7	380.9	—
R*	447.6	667.8	899.7			
T	470.5	672.8				

Table 7.2. Projections of CO₂ to 2100. Again, the ocean-only model (Z) and the feedback cases (R* and T) are kept separate.

The ‘forward’ calculations are defined as those in which CO₂ concentrations are calculated from a given history of emissions. These emission histories are denoted ‘scenarios’ (if related to specific policies) or ‘profiles’ (if they are simply specified as time series). Appendix A specified the use of the six scenarios (IS92a,b,c,d,e,f) from IPCC (1992). (The basis of these scenarios is currently (1994) under review. If they are found to have an inadequate basis, then

they must be regarded as ‘profiles’ —of interest in relation to earlier studies and of interest to the extent that they might match (or bracket) realistic scenarios.)

The emission values defining these IPCC (1992) scenarios are reproduced in Section A.6. Appendix A also specified three ‘science’ emission profiles corresponding to fossil emissions after 2000 being fixed (DEC0%), decreasing at 1% compounded (DEC1%) and 2% compounded (DEC2%). These cases used IS92a between 1990 and 2000.

Tables 7.1 and 7.2 list the projections to 2050 and 2100 for six of the scenarios: IS92a (the de facto ‘business-as-usual’), IS92c, IS92e (the two extremes) and the three ‘science’¹ scenarios, DEC0%, DEC1% and DEC2%. The results fall into two main groups, Models A₂, B₁, B₂, B₃ and G, and the others (E, J, L, T) which give lower projections differing from each other by only a small amount. The reason for this split into two groups has not been ascertained.

Figure 7.1 plots the set of results for IS92a; plots of results of the other IPCC 1992 scenarios are included in Appendix E. Figure 7.2 plots the concentrations resulting from stabilising industrial emissions at 1995 levels (case DEC0%). The cases with specified percentage reductions after 2000 (DEC1% and DEC2%) are plotted in Appendix E. An additional set of forward calculations is specified from scenarios produced by the World Energy Council. These are discussed in Section 12a.

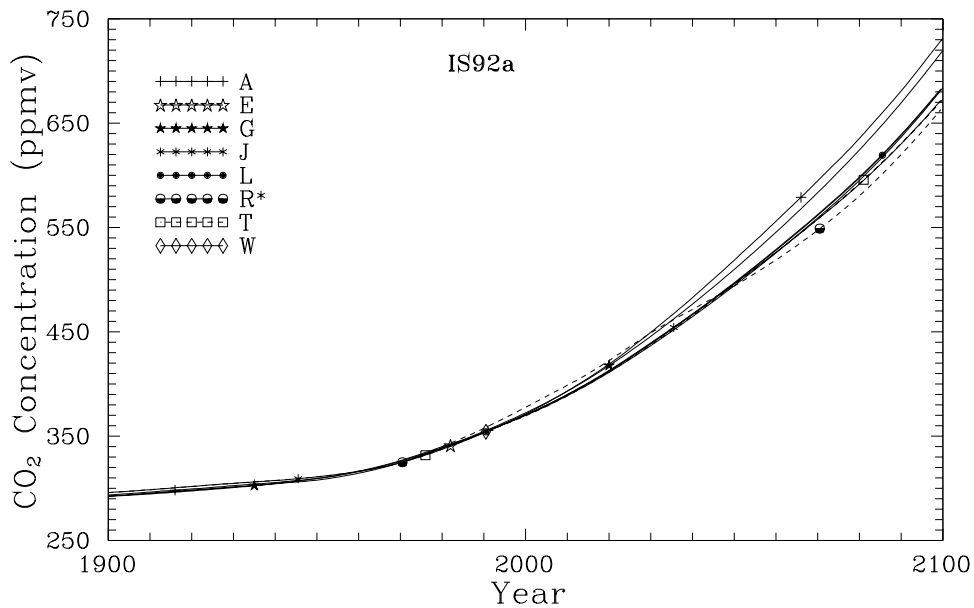


Figure 7.1. Concentrations predicted using IS92a. The curves with short dashes (Models R*, T) were calculated with temperature feedbacks included.

¹Footnote to electronic edition: These cases should have been termed ‘profiles’, see preceding discussion and footnote on page 7.

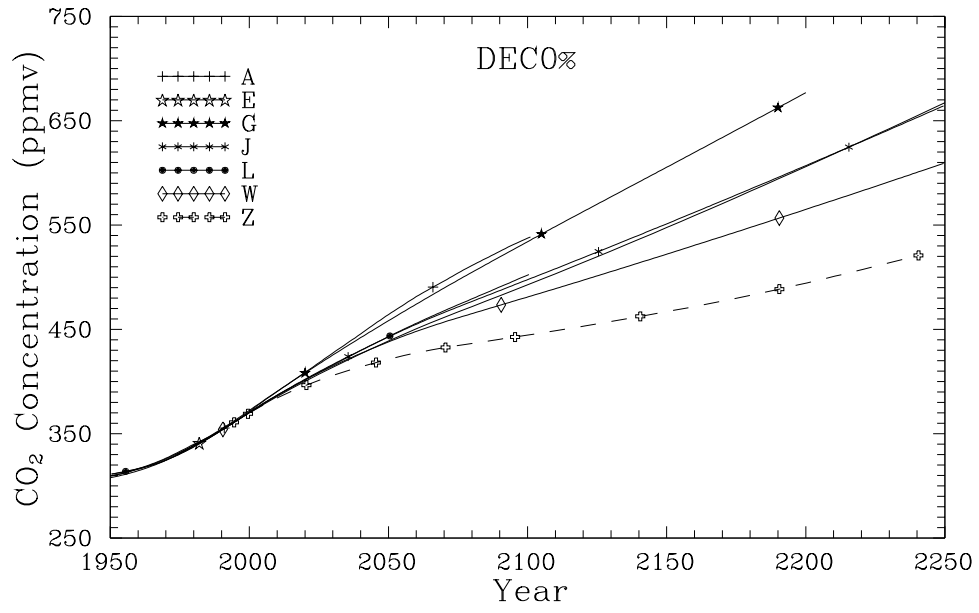


Figure 7.2. Concentrations predicted with emissions fixed at 2000 levels.

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8. Summary of Results for Stabilisation Calculations

Model	S350	S450	S550	S650	S750	DS450	DS550
A ₁	-1.41	6.75	7.38	9.55	11.68	7.26	8.05
	2105	2001	2033	2076	2075	2011	2020
B ₃	0.38	6.37	7.74	9.66	11.53	6.90	7.76
	2098	2002	2075	2077	2075	2011	2066
E	-1.26	6.92	8.42	10.71	12.94	7.57	8.69
	2111	2007	2075	2075	2075	2013	2039
F ₂	-0.54	7.40	10.45	13.43	16.35	8.08	10.66
	2116	2021	2078	2092	2094	2018	2075
H		6.57		9.04			
		2000		2075			
J	-1.12	6.66	8.27	10.59	12.85	7.31	8.43
	2109	2005	2075	2075	2075	2011	2039
L	-1.48	6.82	8.02	10.35	12.64	7.45	8.43
	2108	2005	2075	2075	2075	2012	2033
M		6.26		9.43			
		2000		2076			
Q	-1.06	7.89	9.17	11.54	13.86	8.59	9.72
	2112	2010	2071	2075	2075	2013	2024
R	-0.26	7.15	8.99	10.77	12.69	7.38	9.37
	2100	2040	2056	2058	2059	2037	2043
W	0.03	6.78	9.16	11.44	13.68	7.41	9.26
	2112	2012	2075	2079	2077	2013	2073
T	-1.43	6.82	8.13	10.62	13.13	7.45	8.40
	2106	2005	2075	2079	2081	2012	2029
O		4.77		8.51			
		2007		2079			
P		6.10		7.83			
		1990		2075			
Z	1.05	7.90	11.29	13.66	16.04	8.40	11.45
	2125	2030	2080	2100	2085	2025	2075
B ₁	-0.12	5.65	7.99	9.98	11.70	6.03	7.62
	2076	1998	2104	2104	2104	2008	2104
B ₂	0.52	5.47	8.34	10.33	11.99	5.89	8.01
	2074	2001	2104	2104	2104	2011	2104
C		7.10		16.15			
		2000		2075			
G	0.00	7.10		13.70			
	2020	2000		2050			
V _A		6.90		16.93			
		2002		2047			
V _B		7.48					
		2010					

Table 8.1. Stabilisation cases. Maximum fossil emissions (minimum for S350), in Gt C y⁻¹, and year. The horizontal lines separate groups that are not directly comparable with the top group: the feedback case (T), ocean-only (O, P, Z), and those that fail to fit the specifications (see Section 5). The fossil (industrial) curves can be converted to total anthropogenic emissions by adding the land-use flux specified in Figure B.4. This will shift the positions of the maxima.

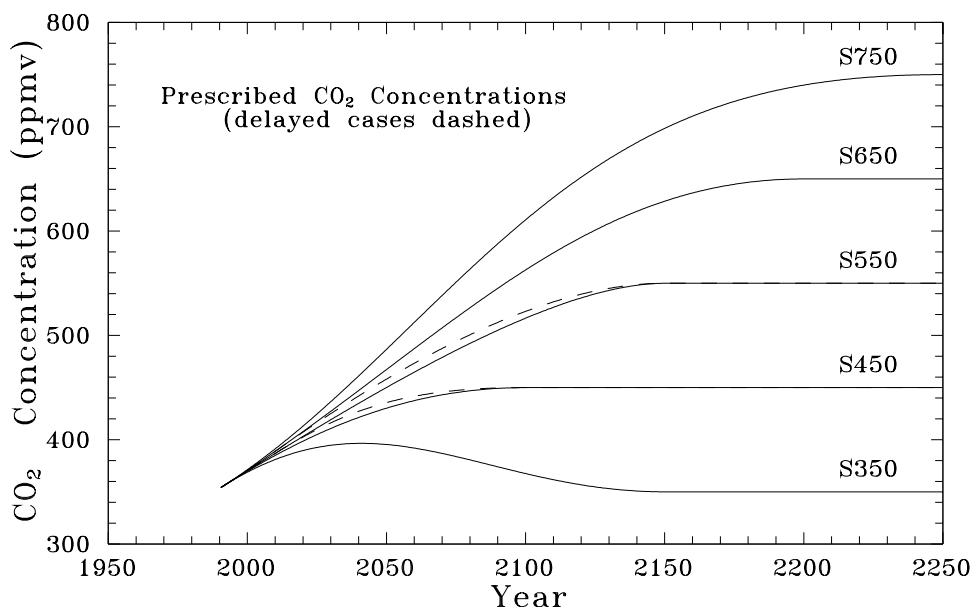


Figure 8.1. Prescribed CO₂ concentrations for stabilisation studies. The dashed curves are the ‘delayed’ cases DS450 and DS550.

This section describes the results of ‘inverse’ calculations which calculated the emissions required to achieve stabilisation of atmospheric CO₂ concentrations via specified concentration profiles. Seven sets of stabilisation profiles were prescribed, with stabilisation at 350, 450, 550, 650 and 750 ppmv. For the 450 and 550 stabilisation cases two concentration pathways were defined: a standard case, and a delayed case in which the concentrations initially followed a higher pathway and were subsequently modified to produce the lower stabilisation level. Figure 8.1 shows the seven prescribed concentration functions. The ‘delayed’ cases are shown as dashed.

Figures 8.2 and 8.3 show the calculated industrial emissions for various models for the S450 and S650 scenarios. Selected values for these cases are tabulated in Appendix D. The results from the two models that included climatic feedbacks are shown with short dashes. The results for the other scenarios are plotted in Appendix E. Tables 8.1 and 8.2 list some key characteristics of the results for all seven scenarios and for all models. These tables include (in their lower sections) results that are not strictly comparable in terms of the specification in Appendix A. Three models are ‘ocean-only’, two include climatic feedbacks, two produced poor fits to the specified concentration histories and one did not ‘balance the current carbon budget’, i.e., an unidentified residual sink was required for balance.

Model	S350	S450	S550	S650	S750	DS450	DS550
A	0.40	1.36	2.14	3.03	4.71	1.35	2.10
B ₃	1.80	2.81	3.59	4.35	5.94	2.80	3.57
E	0.25	1.53	2.57	3.68	5.46	1.51	2.51
F ₂	0.46	2.73	4.96	7.49	10.68	2.70	4.87
H		1.89		3.16			
J	0.34	1.64	2.73	3.88	5.81	1.63	2.67
L	0.31	1.39	2.27	3.33	5.20	1.37	2.22
M		1.55		2.88			
Q	0.60	2.14	3.28	4.49	6.39	2.12	3.22
W	1.02	2.73	4.16	5.58	7.57	2.71	4.10
T	0.21	1.53	2.85	4.51	7.01	1.51	2.80
O		1.95					
P		1.32		2.65			
Z	1.20	4.21	6.28	7.92	9.91	4.18	5.66
B ₁	2.50	3.54	4.40	5.18	6.83	3.53	4.37
B ₂	3.07	4.08	4.87	5.62	7.22	4.07	4.84
C		2.03		2.94			
G	0.00	1.49		1.50			
V _A		2.82		0.37			
V _B		5.55					

Table 8.2. Anthropogenic emissions, in Gt C y⁻¹, for 2200 (equal to calculated fossil, since prescribed land-use flux is zero) for stabilisation cases. The horizontal lines separate groups that are not directly comparable with the top group: the feedback case (T), ocean-only (O, P, Z), and those that fail to fit the specifications (see Section 5).

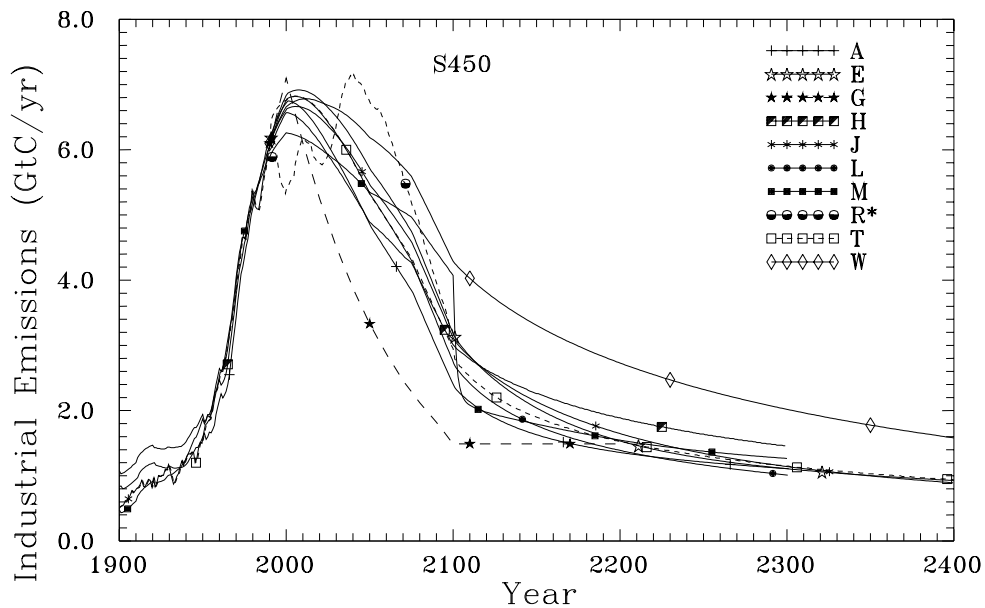


Figure 8.2. Calculated industrial (i.e., fossil) emissions for S450. Model T (short dashes) had temperature feedbacks included. Model G (longer dashes) used a different concentration profile.

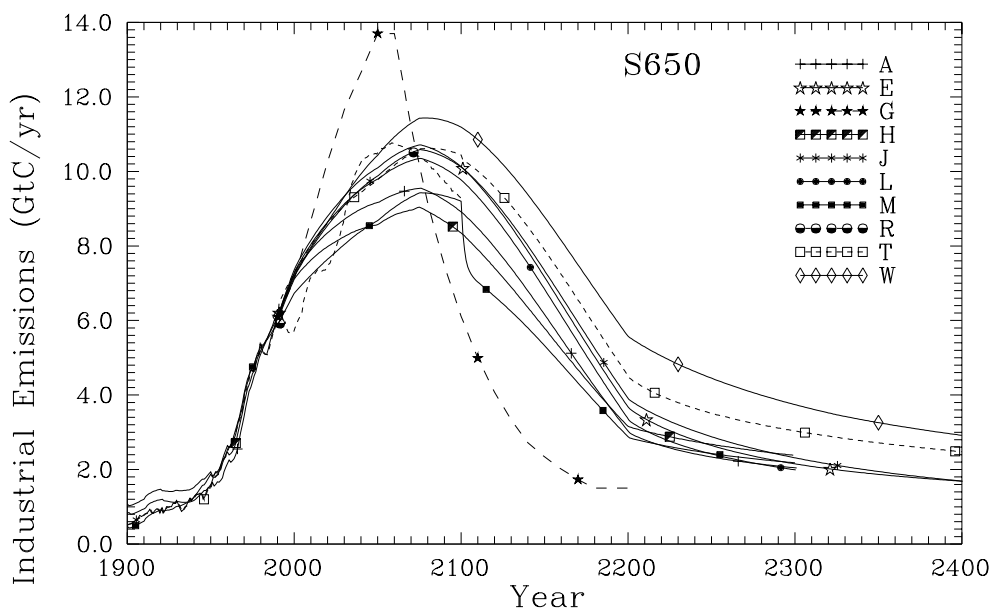


Figure 8.3. Calculated industrial (i.e., fossil) emissions for S650. Model T (short dashes) had temperature feedbacks included. Model G (longer dashes) used a different concentration profile.

For the S650 case, fluxes between the atmosphere and oceans are given in Table 8.3 and fertilisation fluxes are given in Table 8.4.

Model	1990	2000	2050	2100	2200	2300
A	2.25	2.59	3.54	3.65	2.53	1.89
B	2.74	3.15	4.26	4.39	3.07	2.30
E	2.30	2.70	3.70	3.80	2.60	2.00
F ₂	2.27	2.74	4.76	6.02	5.03	3.70
H	1.63	1.87	2.55	2.72	2.18	1.85
J	2.41	2.75	3.68	3.76	2.52	1.84
L	2.38	2.65	3.27	3.22	1.90	1.35
M	1.90	2.18	3.16	3.46	2.70	2.12
O	2.36	2.76	4.18	4.71		
P	2.43	2.78	3.73	3.82	2.63	1.96
Q	2.98	3.46	4.19	3.85	2.13	1.30
R	1.63	1.69	2.57	2.85		
W	2.24	2.59	3.98	4.52	3.55	2.57
Z	4.20	5.09	8.65	10.56	7.92	4.89
T	1.98	2.30	3.20	3.95	3.54	2.80
V _A	4.22	5.35	10.26	7.08	2.80	

Table 8.3. Air-sea fluxes, in Gt C y^{-1} , for S650. All versions of Model B have the same ocean and thus the same air-sea flux in inverse calculations.

Model	1990	2000	2050	2100	2200	2300
A	2.04	2.25	2.19	1.66	0.47	0.15
J		1.97	2.74	2.74	1.36	0.47
T	2.21	2.63	3.31	3.01	1.20	0.50
W	1.85	2.12	2.98	3.07	2.03	1.17

Table 8.4. Fertilisation fluxes for S650.

Figures 8.4 and 8.5 show the effect (in emission terms) of delaying reductions in CO₂ emissions, or more specifically, choosing a higher target and then revising the target downwards. The higher emissions that are allowed in the ‘pre-revision’ period are largely offset by the requirements for greater reductions later. However the integrated emissions allowed in the delayed cases remain slightly higher (by less than 1 years current releases) for an indefinite future period. The real penalty for delay is that the future reductions, implied when the curves in Figures 8.4 and 8.5 go negative, are relative to the reduced emissions shown after 2050 and 2100 in Figures 8.2 and 8.3. In these cases, the marginal cost of achieving greater reductions may be greater. It appears that the result from Model G, which suggests a large penalty in total emissions if reductions are delayed (see dashed curve in Figure 8.6 a), is not representative of the set of model calculations.

Since the prescribed ‘land-use’ flux is the same in all cases, these curves represent the penalty in terms of both total anthropogenic emissions and in terms of calculated fossil emissions.

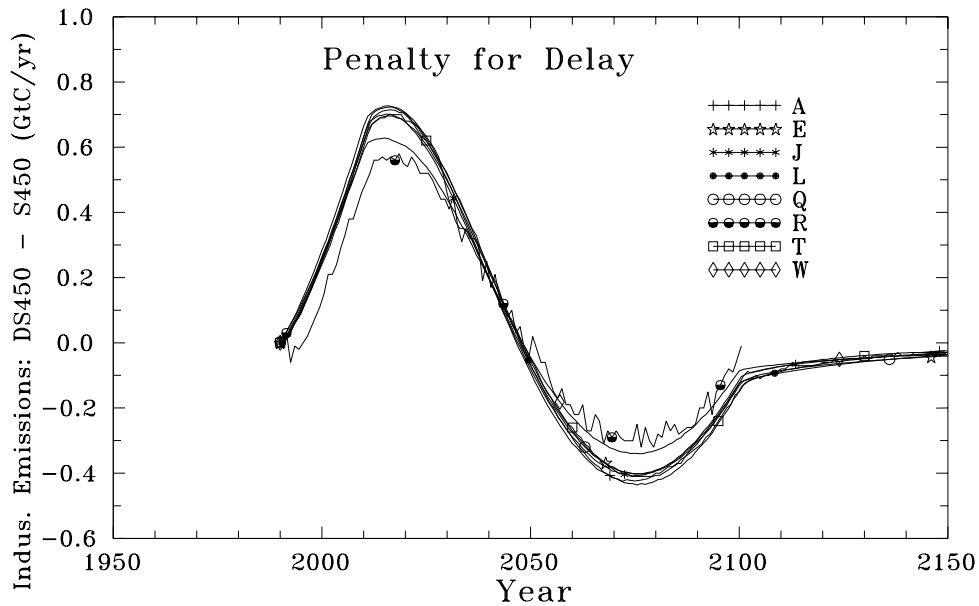


Figure 8.4. Effect of initial delay in moving to stabilisation at 450 ppmv: difference in emissions (DS450 minus S450). Model T was calculated with temperature feedbacks included.

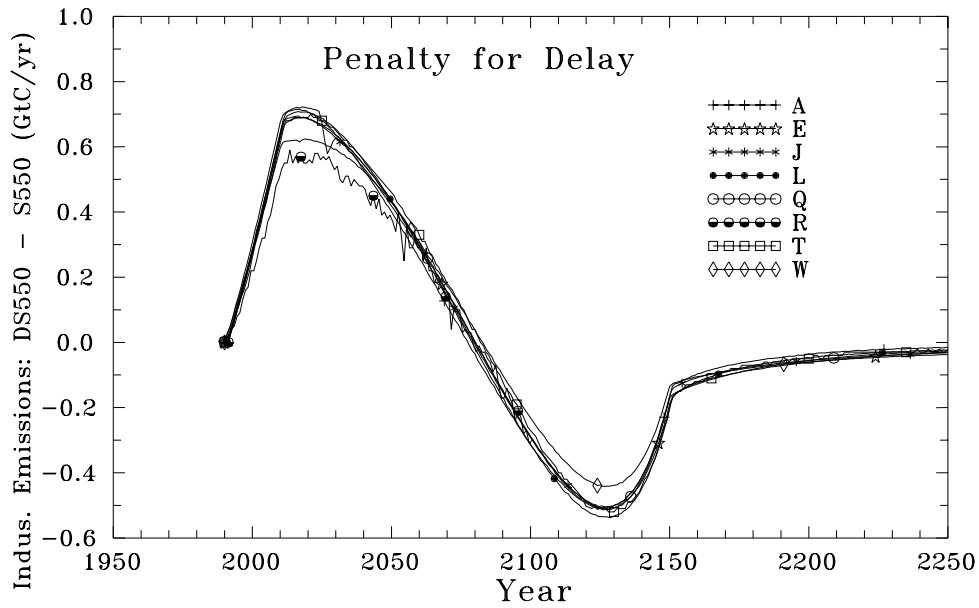


Figure 8.5. Effect of initial delay in moving to stabilisation at 550 ppmv: difference in emissions (DS550 minus S550). The curve with short dashes Model T was calculated with temperature feedbacks included.

An alternative way of characterising the results of these calculations is in terms of cumulative emissions. Table 8.5 shows the cumulative emissions from 1990 to the respective times of stabilisation for the 7 stabilisation profiles.

The two parts of Figure 8.6 present this information over the full time history for the S650 case. Part a shows the integrated emissions from 1990 onwards. Part b (with a factor of 2 change in scale) shows the integrated oceanic uptake from 1990 onwards. Also shown in part b (as the dashed curve) is the atmospheric increase (the prescribed profile, converted to GtC above the 1990 level). For the other stabilisation profiles, the corresponding pairs of plots are included in Appendix E. These are presented as fossil/industrial emissions. The conversion to total anthropogenic emissions involves a small change (82 GtC after 2100, less earlier) that is less than the spread of the results.

A common feature of these results is that, while CO_2 is increasing, the amount of extra CO_2 in the atmosphere, $N_a(t) - N_a(1990) = 2.123[C(t) - C(1990)]$ in GtC, is about half of the integrated anthropogenic emissions. (The land-use component is a small addition to the fossil component shown in the figures). This type of result is often described in terms of an ‘airborne fraction’, r , of CO_2 . This is usually expressed in terms of rates:

$$r = \dot{N}_a(t)/Q(t) \quad (8.1)$$

but it can also be expressed in integral form as

$$\bar{r} = \Delta N_a / \int Q dt = [N_a(t_2) - N_a(t_1)] / \int_{t_1}^{t_2} Q(t) dt \quad (8.2)$$

The two expressions will be equivalent if $N(t)$ and $Q(t)$ increase exponentially, in which case r will be constant in time. Assuming a constant airborne fraction, r , can be a reasonable approximation so long as emissions are increasing, but it starts to break down as emissions decline. As shown in the figures, the integral form, \bar{r} is more nearly constant until stabilisation is reached, at which point $r \equiv 0$.

	S350	S450	S550	S650	S750	DS450	DS550
t_s	2150	2100	2150	2200	2250	2100	2150
A	165.1	551.5	1052.6	1566.2	2078.6	558.3	1063.6
H		561.9		1484.7			
J	210.9	599.8	1158.3	1743.4	2331.5	607.0	1171.0
L	182.8	588.9	1128.7	1686.7	2243.1	595.7	1139.9
Q	301.5	711.9	1309.6	1931.6	2552.3	720.3	1323.3
R		623.8				631.2	
T	192.4	593.7	1159.6	1799.1	2503.4	601.4	1173.9
W	345.7	666.2	1277.6	1937.4	2618.7	674.8	1293.3

Table 8.5. Cumulative fossil emissions from 1990 to the time of stabilisation, t_s . Cumulative anthropogenic emissions are greater by 82 GtC.

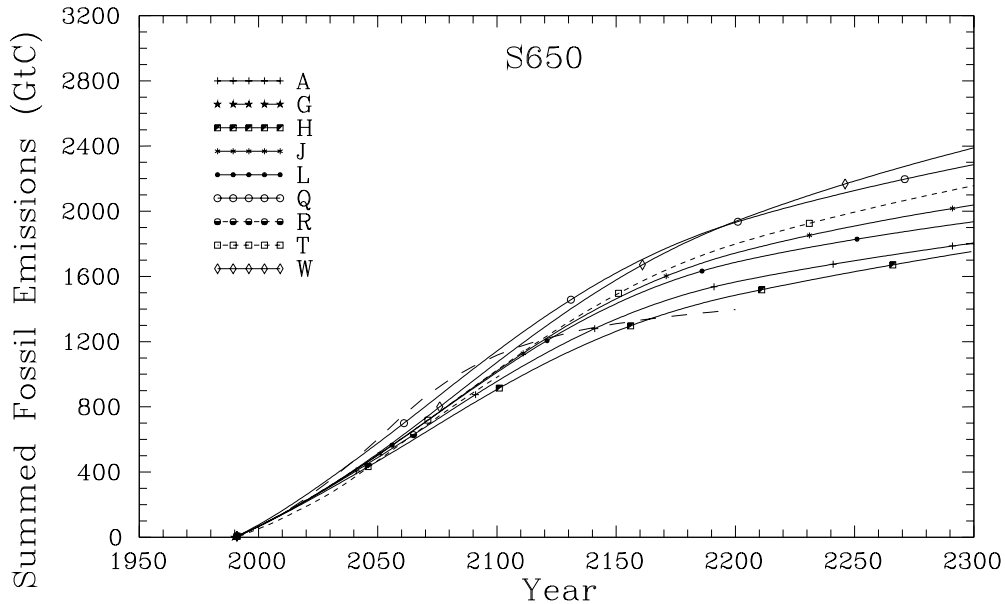


Figure 8.6a. Cumulative fossil emissions after 1990, for S650. Long-dashed curve is from Model G using alternative stabilisation profile (Appendix F). Integrated anthropogenic emissions are higher by 82 GtC after 2100 and by smaller amounts between 1990 and 2100.

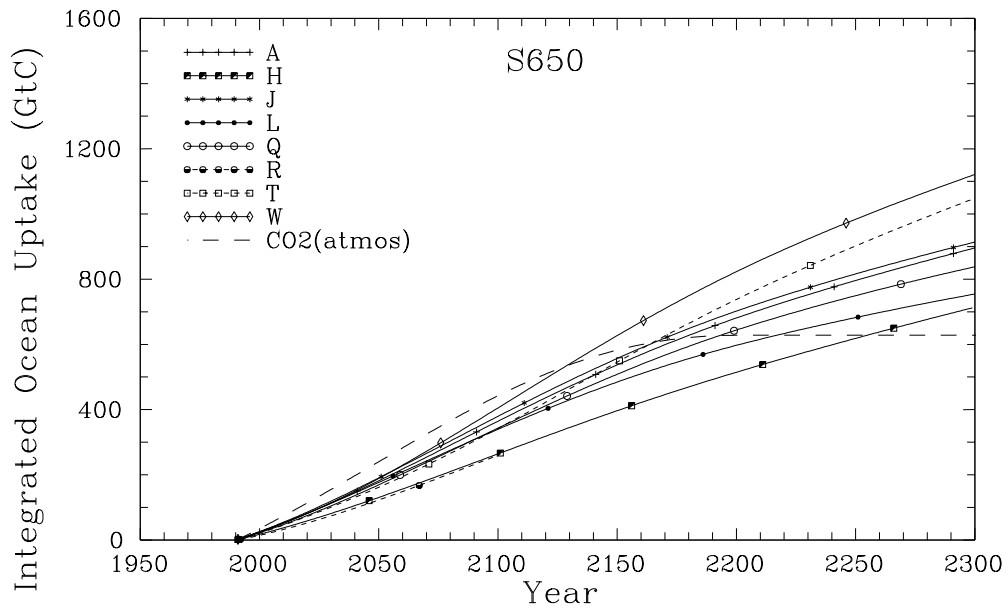


Figure 8.6b. Cumulative oceanic uptake after 1990 for S650. Long-dashed curve is atmospheric increase from 1990, from S650 curve in Figure 8.1.

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9. Summary of Results for Response Functions

9a Definitions and results

Impulse response functions can be a powerful way of describing the behaviour of the atmospheric CO₂ system (Oeschger and Heimann, 1983). Impulse response functions have been calculated as perturbations from two specific cases: an ‘equilibrium response’ in which the background was zero emissions and a ‘perturbation response’ in which the background was the emissions deduced from the S650 concentration profile. The responses were calculated by adding 10 GtC to the background emissions (in 1995 for the perturbation case), integrating forward and calculating the concentration differences from the background case.

Equilibrium response functions have been calculated using Models E, G, H, J, L and W. Perturbation calculations have been undertaken with Models E, H, J, L, R and W.

The response function, $G_a(t)$, can then be evaluated as

$$G_a(t) = 2.123[C(t) - C_{\text{background}}(t)]/10.0 \quad (9.1)$$

$G(t)$ is taken to be 1.0 at $t = 0$, defined as mid-1995 for the perturbation case. The most widely quoted ocean response function is

$$G_O(t) = 0.131 + 0.201e^{-t/362.9} + 0.321e^{-t/73.6} + 0.249e^{-t/17.3} + 0.098e^{-t/1.9} \quad (9.2)$$

from the ocean GCM of Maier-Reimer and Hasselmann (1987) relative to the pre-industrial state. This response function is used as the basis for describing oceanic uptake in Models T and W.

The equilibrium and ‘S650’ response functions are tabulated in Tables 9.1 and 9.2, and plotted in Figures 9.1 and 9.2 respectively.

Model	0	10	25	50	100	200	300	400	500
E	1.0	0.546	0.386	0.289	0.234	0.204	0.187	0.174	0.163
G	1.0	0.639	0.552	0.497	0.435	0.369	0.329	0.299	0.276
H	1.0	0.430	0.284	0.217	0.174	0.141	0.126	0.117	
J	1.0	0.560	0.410	0.316	0.248	0.204	0.185	0.172	0.163
L	1.0	0.643	0.459	0.354	0.302	0.254	0.228	0.212	0.202
W	1.0	0.629	0.442	0.309	0.225	0.176	0.155	0.143	0.135

Table 9.1. Equilibrium response function, at selected values of t in years, calculated relative to constant pre-industrial concentrations.

Model	0	10	25	50	100	200	300	400	500
E	1.0	0.624	0.493	0.419	0.401	0.425	0.408	0.389	
H	1.0	0.679	0.567	0.540	0.560	0.562	0.531		
J	1.0	0.628	0.507	0.435	0.401	0.393	0.376	0.359	0.348
L	1.0	0.695	0.555	0.495	0.477	0.459	0.424	0.399	0.386
R	1.0	0.786	0.616	0.531	0.488				
W	1.0	0.709	0.555	0.430	0.368	0.347	0.320	0.280	0.247

Table 9.2. Perturbation response function, calculated relative to S650.

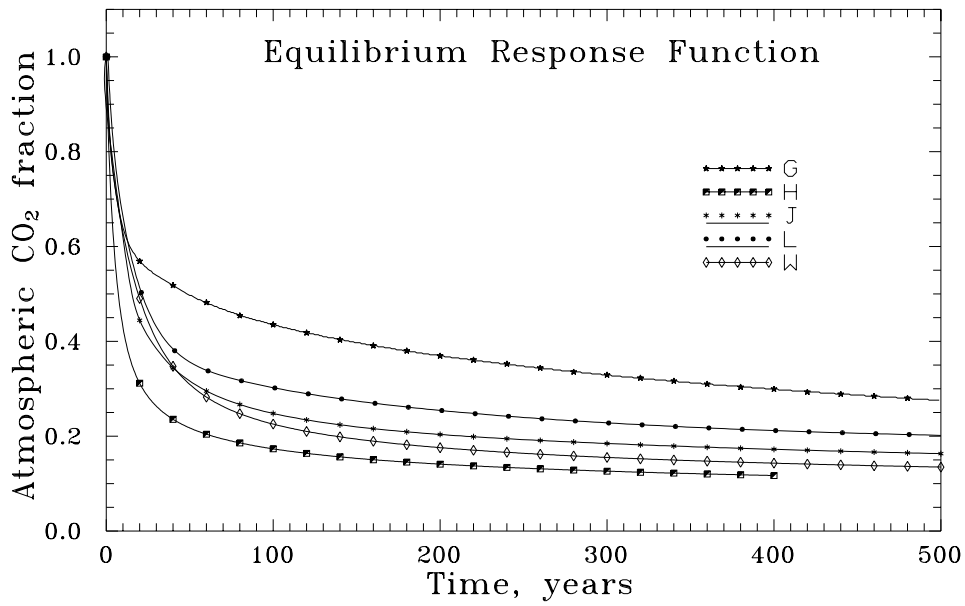


Figure 9.1. Impulse response relative to pre-industrial state.

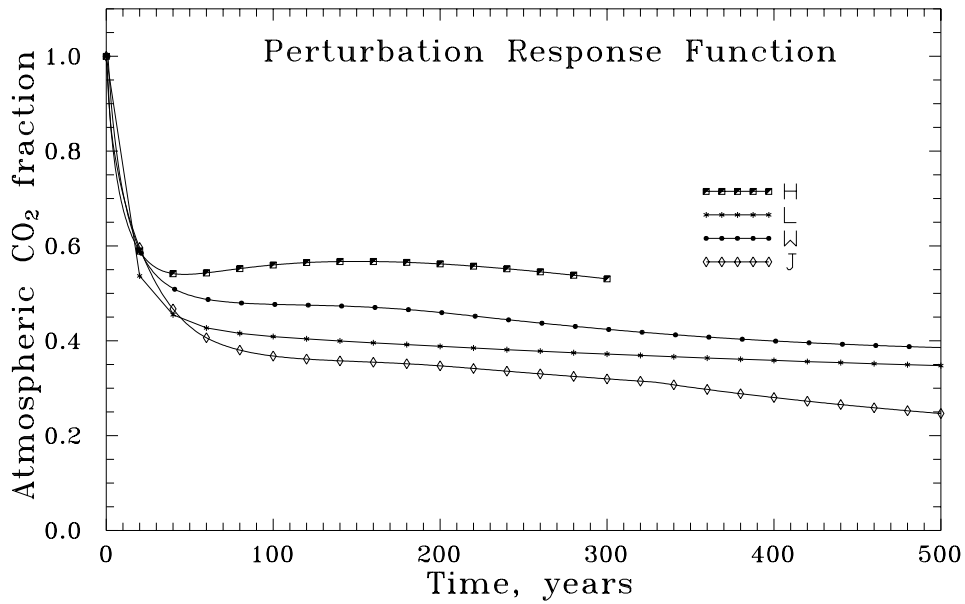


Figure 9.2. Impulse response relative to S650.

The calculation of global warming potentials requires the evaluation of the time-integrated CO_2 radiative forcing. With the radiative forcing, F_{CO_2} , of CO_2 (in Wm^{-2}) approximated by (Shine et al: IPCC, 1990, p41)

$$F_{\text{CO}_2} = 6.3 \ln \frac{C(t)}{C(0)}, \quad (9.3)$$

the integrated extra forcing per Gt of carbon is

$$\int_0^\tau \Delta F_{\text{CO}_2} dt' = \int_0^\tau \frac{6.3}{2.123 C(t')} G_a(t') dt' \quad (9.4)$$

Again $t' = 0$ is defined as mid-1995. Integrated forcings have been calculated for the five models listed above.

9b The reference response for GWP calculations

The Global Warming Potential (GWP) is a numerical index that is designed to assist in comparisons of the relative radiative importance of various greenhouse gases. The index has to be defined for specific time intervals of interest. The definition of the GWP of constituent X (for time horizon τ) is

$$\text{GWP}_{X,\tau} = \frac{\int_{t_X}^{\tau+t_X} \Delta F_X(t', t_X) dt'}{\int_{t_r}^{\tau+t_r} \Delta F_{\text{ref}}(t', t_r) dt'} \quad (9.5)$$

where the ΔF terms give the extra radiative forcing at time t' due to a unit input of constituent X at time t_X . Note that this definition has an implicit dependence on both t_X and t_r , the initial impulse times for X and the reference. These are important if non-linearities occur in either the emission-concentration or the concentration-radiative forcing relationship. The IPCC (1990) definition was to use CO_2 as the reference gas.

The difficulties with this definition were:

- Non-linearities in the response of CO_2 to emission changes mean that in equation (9.3) defining ΔF_{CO_2} for CO_2 , the term $G_a(t)$ (equation 9.1) depends on the background concentration profile.
- The concentration dependence of the radiative forcing of CO_2 (equation 9.3) will give an additional dependence on CO_2 profile for the CO_2 forcing.
- Uncertainties in the carbon budget translate into additional uncertainties in the CO_2 response (see Section 11). Specifically, the results depend on how the contemporary budget is balanced *vis-a-vis* the incorporation of a CO_2 -fertilisation effect.
- The three dependences above will propagate into *all* GWP calculations if the actual forcing from CO_2 is used as the reference case for GWP definitions.

In order to address these difficulties, the IPCC report on Radiative Forcing of Climate Change (IPCC, 1994, chapter 5) adopted the following procedure:

- The reference case (defining the denominator of 9.5) would be an idealised CO_2 radiative forcing.
- A particular background CO_2 concentration profile would be specified, so as to avoid the concentration dependence of both the response and the radiative effects.

- The background CO₂ concentration profile chosen as the reference was a constant concentration (at 354.17 ppmv) from 1990 onwards. (This avoids the potential dependence of t_r noted in connection with 9.5).
- The reference gas impulse response would be defined as the effect of a pulse release in 1995 as calculated with a representative model.
- On the basis of the results of the calculations presented in this report, Model J, the model described by Siegenthaler and Joos (1992), was chosen as the reference case.

The response function for the reference case is tabulated in Table 9.3 and plotted in Figure 9.3 (together with other response functions calculated using Model J).

Time	0	20	40	60	80	100	200	300	400	500
G_a	1.0	0.515	0.412	0.359	0.327	0.305	0.253	0.231	0.217	0.206

Table 9.3. Response function for Model J, calculated by adding a pulse in 1995 to the emissions required to give constant concentrations (354.17 ppmv) from 1990 onwards. Note that the differences from Table 9.1 arise from the higher background concentration which in turn requires non-equilibrium conditions at the time of the pulse.

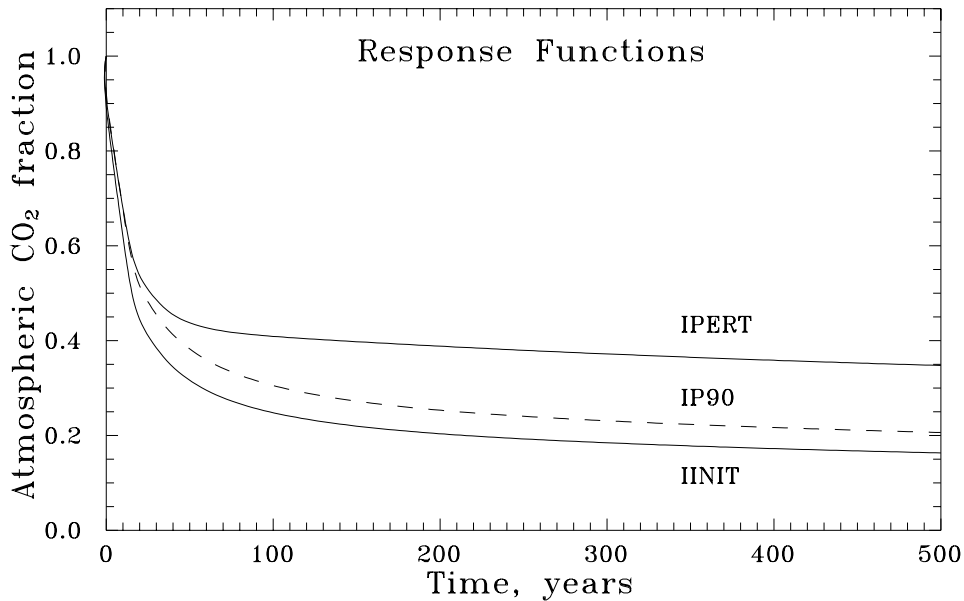


Figure 9.3. Response functions for Model J. IINIT is relative to the pre-industrial case, IIPERT is relative to S650 and IIP90 is the case defined as the reference for GWP, i.e., relative to constant concentrations from 1990.

The response functions for Model J were parameterised as sums of exponentials in the form

$$G_a(t) = a_0 + \sum_j a_j \exp(-t/\tau_j) \quad (9.6)$$

with the a_j and τ_j as specified in Table 9.4.

j	0	1	2	3	4
IINIT					
a_j	0.130164	0.333279	0.260540	0.165742	0.110275
τ_j	—	4.144656	18.587414	58.455562	414.152957
IPERT					
a_j	0.297144	0.202022	0.365643	0.135191	—
τ_j	—	3.054167	16.5172219	506.977719	—
IP90					
a_j	0.168312	0.261529	0.246715	0.197060	0.126483
τ_j	—	3.899498	18.664312	59.315997	415.962281

Table 9.4. Coefficients defining the parameterisation of the response functions calculated using Model J. IINIT is relative to the pre-industrial case, IPERT is relative to S650 and IP90 is the case defined as the reference for GWP, i.e., relative to constant concentrations from 1990.

9c. Combining response functions

The analysis in the previous sections has involved the response of the combined terrestrial-plus-oceanic system to perturbations in atmospheric CO₂ levels. However, it can be useful to study the separate responses of oceanic and terrestrial components, firstly as a basis for combining results from components of a single model and secondly for relating results of full models to the results of partial models. This section shows how sub-system responses are related to the total response.

The general equation governing concentration changes may be written as

$$\frac{d}{dt}N_a(t) = Q(t) - S_{\text{fert}}(t) - S_{\text{ocean}}(t) = Q(t) - \frac{d}{dt}N_b(t) - \frac{d}{dt}N_o(t) \quad (9.7)$$

where N_b denotes changes in terrestrial carbon without any land-use change.

Assume that we have a linear system consisting of atmosphere, ocean and biosphere. From the definition of the atmospheric impulse response function, $G_a(\tau)$, as a Green's function, we may write:

$$N_a(t) = \int_0^\infty G_a(\tau) Q(t - \tau) d\tau \quad (9.8a)$$

where $N_a(t)$ represents the excess atmospheric CO₂ mass at time t and $Q(t)$ the atmospheric CO₂ source.

Treating the terrestrial and oceanic components separately, the atmospheric concentrations are also linear in the sources — the sources for each component being the anthropogenic source

plus the carbon flux from the other component. We can define partial Green's functions, $G_{a:bio}$ and $G_{a:oc}$ such that:

$$N_a(t) = \int_0^\infty G_{a:bio}(\tau) [Q(t - \tau) - S_{ocean}(t - \tau)] d\tau \quad (9.8b)$$

and

$$N_a(t) = \int_0^\infty G_{a:oc}(\tau) [Q(t - \tau) - S_{fert}(t - \tau)] d\tau \quad (9.8c)$$

where $G_{a:oc}$ and $G_{a:bio}$ are the respective responses of the oceanic and terrestrial components to a pulse source.

The equations (9.7, 9.8a,b,c) involving convolution integrals can be solved by taking Laplace transforms and solving the resulting algebraic equations for G_a . In practice, the partial impulse response functions are given in numerical form, calculated using the models for each component separately and applying pulse sources. By numerical fitting these can be represented as a series of exponential functions (plus possibly a constant offset). The series can be easily transformed and algebraically solved for the Laplace transform of G_a . Since only exponentials are involved, rational functions of p result. These are readily transformed back into a series of exponentials.

Using h , or more specifically $h(p)$, to denote the Laplace transform of a function $H(t)$ we obtain the transforms of equations (9.8a–c) as equations (9.9a–c)

$$n_a = g_a(p) q(p) \quad (9.9a)$$

$$n_a = g_{a:bio}(q - pn_o) \quad (9.9b)$$

$$n_a = g_{a:oc}(q - pn_o) \quad (9.9c)$$

and the transform of (9.7) is

$$pn_a = q - pn_b - pn_o \quad (9.10)$$

Eliminating n_o and n_b gives:

$$pn_a = n_a/g_{a:bio} + n_a/g_{a:oc} - q(p) \quad (9.11)$$

so that for the full atmospheric response function, $G_a(t)$, we have from (9.10)

$$g_a = p^{-1} \left[\frac{1}{p g_{a:oc}} + \frac{1}{p g_{a:bio}} - 1 \right]^{-1} = \frac{g_{a:oc} g_{a:bio}}{g_{a:oc} + g_{a:bio} - p g_{a:oc} g_{a:bio}} \quad (9.12)$$

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10. Assessment of Results

10a. General issues

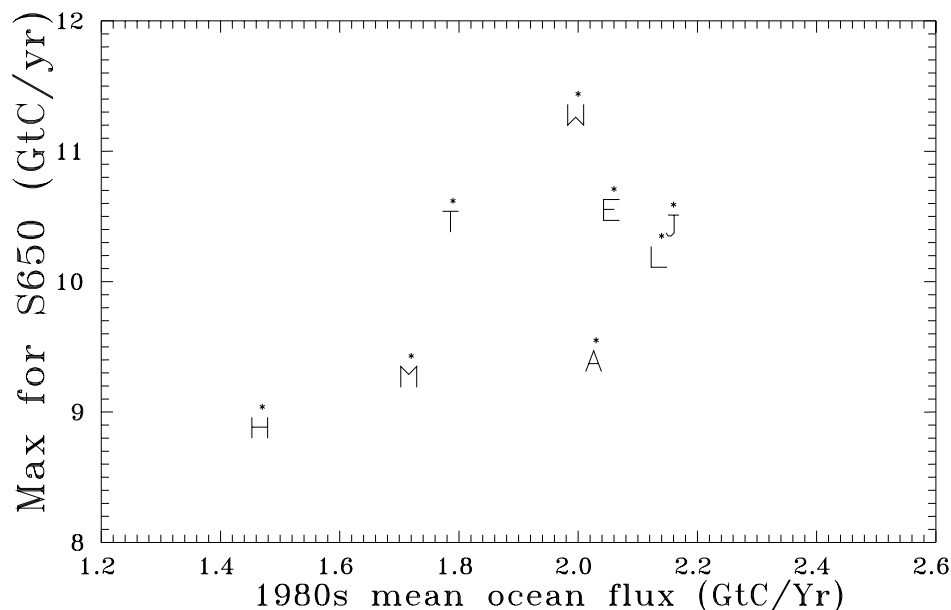


Figure 10.1. Relation between future fossil emissions and current oceanic uptake.

The results tabulated in the preceding sections and the appendices show a relatively wide range of projections. It is, however, possible to discern a few general characteristics.

The forward projections are very tightly grouped, while the stabilisation cases show a much wider proportional spread. This comes from two well-understood mathematical characteristics of the problems. Firstly, inverse calculations (i.e., the stabilisation calculations) amplify uncertainties much more than forward calculations. Secondly, since all the models are tuned to fit the historical record which has been a period of increasing emissions, they will tend to agree with each other (and be expected to be most accurate) when projecting the consequences of a similar period of future growth in emissions. This is a consequence of the models being only weakly non-linear and the growth being near to exponential. The differences between models will become apparent when they are used for calculations (whether forward or inverse) involving periods of significant decreases in emissions as required for stabilisation.

The curves for the integrated emissions (Figure 8.6a, b for S650 and Figures E.13a,b to E.16a,b for the other cases) show that for the distant future, the terrestrial storage component plays a more minor role than in many estimates of the current atmospheric budget. The bulk of the fossil emissions are partitioned (roughly equally) between the atmosphere and the oceans. This suggests that the current value of the ocean carbon uptake may be related to the long-term partitioning between the atmosphere and ocean and therefore also related to the emissions consistent with specified atmospheric concentrations. This is explored in Figure 10.1 which plots the maximum emissions for S650 against the mean ocean carbon uptake of the 1980s for those models for which the information was provided. Figure 10.1 shows a general positive

correlation, with a scatter that indicates that other inter-model differences are also important. The results for Model B (not shown) lie well away from the general trend, but these are not comparable because of the different way in which the atmospheric budget is treated. For model A, the modellers (J. Lloyd, personal communication) regard the departure from the general trend as due to the mechanistic formulation of the terrestrial component, rather than the use of the low eddy-diffusion coefficient discussed in Section 6.

10b. The IPCC report on Radiative Forcing of Climate Change

This report documents the calculations that were contributed in response to distribution of the specifications contained in Appendix A. The purpose of this exercise was to obtain input for the IPCC report on Radiative Forcing of Climate Change (IPCC, 1994) and the Full Scientific Assessment (IPCC, 1995). These reports contain only a subset of the results presented here, although the discussion drew on the wider set of results. As well as being selective in the cases displayed, the IPCC reports also involved selection of models. The IPCC reports included all models that complied with the specifications. Those excluded were:

Model C This did not partition the fluxes and so the degree of compliance with the budget specification could not be defined.

Model F Terrestrial biota only and so only a small number of the results were applicable.

Model G The inverse calculations failed to follow the specified profiles.

Models R* and T Included climatic feedback and so are not directly comparable to other results.

Models O, P, V and Z These were ocean-only models and so only a small number of results could be used.

We therefore used Models A, E, H, J, L, M, Q, R and W for all cases where results were contributed. We also include the forward calculations from Model G. For the inverse calculations we also use the ocean flux calculations from O, P, V and Z and the fertilisation fluxes from F. The ocean-only models and the biota-only model could also be used for determining the respective 'sub-system' impulse responses. Models F₂ and Z were received too late for full discussion.

One important difference between the presentation used in this report and IPCC (1994) is that the latter presents results in terms of total anthropogenic fluxes, $Q(t)$. The reasons for this are:

- The total flux is the more relevant quantity for the objectives of the Framework Convention on Climate Change.
- The calculated totals are largely independent of the partitioning between fossil and land-use and so are of greater generality than is implied by the form or presentation used in this report.

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11. Assessment of Uncertainties

11a. General issues

A very important part of this modelling exercise is the assessment of the uncertainties involved in the CO₂ projections. Some of the key contributions to uncertainties in the model results are:

- Model error;
- Budget uncertainty;
- Imprecise calibration.

There are many aspects of uncertainty analysis and a range of options exists for addressing them:

1. We can investigate the model-dependence by comparing the results of a set of carefully standardised cases. Much of the present exercise adopts this approach.
2. The consequences of the underlying assumptions can also be explored using a set of standardised cases.
3. The sensitivity of the results to variations in model parameters can be explored by systematic exploration of the parameter space (either deterministically or stochastically).
4. A more relevant refinement of (3) is provided by assessing the sensitivity to those sets of parameter variations that lead to results consistent with observations. This can be assessed using a statistical approach to model calibration. Rather than determine fixed sets of parameters seeking exact fits to specific data items, models can be calibrated by determining sets of compatible parameter values that give model results within an acceptable range of observed values.

11b. Relation to the modelling framework

One way of specifying a systematic approach to the analysis of uncertainty is to express it in terms of the general modelling framework described in Section 3b above. The response function form of the carbon cycle may be expressed as

$$N_a(t) = 2.123[C(t) - C_0] = \int_0^\infty G_a(\tau) Q(t - \tau) d\tau + \epsilon(t) \quad (11.1a)$$

or in terms of the Laplace transform:

$$n_a(p) = g_a(p) q(p) \quad (11.1b)$$

where we have extended the idealised ‘error-free’ forms used in the discussion above and acknowledged that actual carbon concentrations will include a ‘noise’ component, $\epsilon(t)$, which is not amenable to modelling.

The equations for rates of change lead to the expression for the airborne fraction defined by (8.1) as

$$r = pn_a(p)/q(p) = pg_a(p) \quad (11.2)$$

(see Enting, 1990). If $N_a(t)$ and $Q(t)$ have exponential growth (with the same time constant) then r is a constant.

The uncertainties in predictions made with the model reflect the uncertainties in the response G_a , either explicitly as a response function or, more commonly, implicitly in terms of the parameters of a model.

- The first question to arise is how well even a single response can be estimated from the observational data, i.e., how well can $g_a(p \approx 0.025)$ (and thus the airborne fraction) be estimated. In the specifications from Appendix A, the suggestion that reasonable fits to the observational data have growth rates for 1990 in the range 1.7 ± 0.1 ppmv y^{-1} addresses this aspect of uncertainty. It implies an uncertainty of $\pm 6\%$ in the airborne fraction. Such estimates of uncertainty will be applicable to calculations where future emissions grow in a manner comparable to past growth.
- For emission profiles that depart from near-exponential growth, calibrating $g_a(p)$ for a single p value is not enough. A more complete specification is required. Given the uncertainties about the current atmospheric carbon budget, a major part of the uncertainty in determining $G_a(t)$ will reflect the partitioning of the sink between oceanic and terrestrial components, i.e., in terms of the notation of Section 9c, the relative contributions of $g_{a:oc}$ and $g_{a:bio}$ to the combined response

$$g_a = \frac{g_{a:oc} g_{a:bio}}{g_{a:oc} + g_{a:bio} - pg_{a:oc} g_{a:bio}} \quad (9.9d)$$

The specifications in Appendix A do not directly address this aspect of calibration uncertainty. Some assessment can be made by comparing the results from different groups. It is to be expected that this ambiguity will affect calculated values to an increasing extent as emission profiles depart from the past pattern of continuing growth.

- Up to this point, it has been assumed that the calibration has been undertaken with the past anthropogenic source function, $Q(t)$, exactly known. In practice this is not the case. For the ‘land-use’ component there is considerable uncertainty. Referring back to equation (11.1b), proportional uncertainties in the forcing will have the same effect on estimated responses as the same proportional uncertainty in the response, n_a . The range 1.6 ± 1.0 implies an uncertainty of $\pm 15\%$ in the current anthropogenic emissions, and thus in the airborne fraction.

The instructions in Appendix A provide for the investigation of this aspect of uncertainty by proposing a mean value of $1.6 \text{ Gt C } y^{-1}$ for D_n over the 1980s with values of 0.6 Gt C

y^{-1} and 2.6 Gt C y^{-1} proposed for exploring the effect of this aspect of budget uncertainty. These are discussed in Section 11d below and they confirm the simple analysis based on Laplace transforms.

- A major contribution to the uncertainty concerns the modelling framework that we have adopted. It is inherent in the assumption that discrepancies in the current atmospheric carbon budget are due to processes that can be explicitly modelled and that such modelling can be extended into the future. More specifically, we have required that the imbalance is to be accounted for in terms of CO_2 -induced growth. This assumption corresponds to taking the residual flux S_{resid} in equation (2.1) as being zero. If this assumption is inadequate then the accuracy of future projections will be affected in two ways: firstly through the effects of S_{resid} in the future, and secondly, and more importantly, through the effects of using an incorrect budget in the calibration. The uncertainties arising from this second cause will be equivalent to those arising from the other cases of incorrect budget estimates (i.e., uncertainties in $C(t)$ and $D_n(t)$) described above.
- The final aspect of uncertainty is one that is not amenable to systematic analysis: the question of errors in model structure. The comparison between the different model results presented in this report provides examples of a range of different model structures. However, this can not be readily converted into a quantitative assessment of uncertainty. The difficulties are:
 - The relatively small number of models may not adequately sample the range of variability so that the range of variability underestimates the range of uncertainty;
 - The possibility that some key process has been omitted in all models so that the set of results is systematically biased;
 - There is the possibility that some of the highly parameterised models are so crude that they cannot properly represent key processes. In this case, the range of uncertainty based solely on ‘good’ models may be less than the spread of the results presented here.

11c. Previous studies

There have been a number of previous studies that have either compared a range of models or studied uncertainties within the framework of a single model.

Killough and Emanuel (1981) compared five ocean models, each calibrated with ^{14}C . In the terminology of this report, the calculations used inverse initialisations (deducing a terrestrial source/sink history) with forward calculations for the future, and assuming no change in biomass in the future. In spite of the fact that the models had cumulative oceanic uptakes ranging over a factor of 3 for the pre-1975 period, the predictions for future concentrations had a relatively small spread ($1800 \pm 200 \text{ ppmv}$ for 2100 with a logistic release function). These models had airborne fractions significantly greater than those occurring in the present set of calculations.

Laurmann and Spreiter (1983) performed an extensive study of the uncertainties in predictions of future CO₂. Their conclusion was that the proportional uncertainties were small in the cases of growing releases unless the growth rate dropped below 1.5%y⁻¹, and until CO₂ concentrations exceeded 4 × pre-industrial levels. They included studies of the effects of (i) linearising the CO₂-fertilisation function (ii) linearising the buffer factor calculations, (iii) changing the exponential growth rate (including the transient effect). They noted larger proportional uncertainties for lower growth rates (including the extreme case of setting future emissions to zero). They noted the potential effect of uncertainties in the deforestation rate on the calibration. However, their quantitative studies of this were confined to analysing the bias introduced by ignoring possible pre-1958 deforestation. Their main conclusion was that for generally increasing releases, the behaviour of the system implied a nearly constant airborne fraction.

Gardner and Trabalka (1985). Perhaps more important than the extent to which the results depend on the model parameters is the question of the sensitivity to those sets of parameter variations that are consistent with the observational data. To address this question, Gardner and Trabalka (1985) used a Monte Carlo approach, generating sets of randomly distributed parameters and looked at the variability of results for the subset of cases that were consistent with observations.

Enting and Pearman (1983, 1986, 1987). Enting and Pearman embedded the sensitivity analysis within the model calibration procedure. This approach has been applied to the case with the box-diffusion model used to calculate the IS92a scenario (Enting and Lassey, 1993). They investigated the question of how much variation was possible in the atmospheric concentration for the year 2100, subject to retaining a specified degree of agreement between the model results and the calibration data.

There have also been several studies that have analysed the uncertainties in projections of CO₂ in terms of the direct sensitivities to model parameters: Kandlikar et al. (1992), Filar (1993), Parkinson et al. (1993), Wigley (1993), Rotmans and den Elzen (1993).

11d. Sensitivity to carbon budget

The instructions in Appendix A prescribe a specific set of calculations to address this question. The budget uncertainty is characterised in terms of uncertainty in the land-use component: the specified calculations require the use of 0.6 and 2.6 Gt C y⁻¹ for the 1980s in place of the 1.6 Gt C y⁻¹ specified as the standard case. In addition, alternative fits to the CO₂ data were provided giving 1990 growth rates of 1.6 ppmv y⁻¹ and 1.8 ppmv y⁻¹ in place of the standard 1.7 ppmv y⁻¹ (see Figure B.2).

Various sensitivity calculations have been performed using Models J, W and Z.

Land-use Flux, Gt C y ⁻¹	0.6	1.6	2.6
β -factor	0.127	0.380	0.626
IS92a*			
<i>C</i> (2050)	518	499	486
<i>C</i> (2100)	748	688	643
S450			
<i>E</i> (2100)	2.28	3.09	3.78
<i>E</i> (2200)	1.37	1.64	1.91

Table 11.1. Results from Model J indicating sensitivity to uncertainties in current flux from land-use change.

Table 11.1 shows results from Model J for the IS92a* (i.e., IS92a with the land-use flux going to zero in 2100) forward calculation and the S450 inverse calculation. The 1.6 ± 1.0 Gt C y⁻¹ range on the land-use flux corresponds to a $\pm 15\%$ range on the 1980s' anthropogenic forcing. The discussion above would suggest that this would correspond to a $\pm 15\%$ range in the future airborne fraction. The concentration changes, relative to 1990, confirm this expectation. For the S450 calculation, where the emission pattern differs greatly from the continuing growth of the IS92a* scenario, the range of variation in calculated emissions is proportionally larger than the range of variation in current anthropogenic forcing. This example quantifies the qualitative discussion of this aspect in Section 11b.

These calculations enable us to assess the significance of revised estimates of the current carbon budget. The IPCC (1994) report uses a mean 1980s' rate of CO₂ increase of 1.53 ppmv y⁻¹ rather than the 1.59 ppmv y⁻¹ specified for the model calculations. The revised estimate of the flux from land-use change is 1.1 Gt C y⁻¹ rather than 1.6 Gt C y⁻¹, i.e., anthropogenic fluxes of 6.6 Gt C y⁻¹ rather than 7.1 Gt C y⁻¹. These changes to the growth rate and the anthropogenic forcing imply changes of -4% and $+7\%$ in the airborne fraction for the 1980s, relative to that used in the modelling. Thus models calibrated with the IPCC (1994) budget should be expected to have airborne fractions 3% higher than used here and thus give calculated anthropogenic emissions that are about 3% lower than those presented here. The differences can be expected to be somewhat larger for cases stabilising at the lower concentration levels, but in all cases the offset is expected to be much less than the spread of values from the different models.

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12. Additional Calculations

In addition to the calculations specified in Appendix A, a number of additional calculations were contributed. In this section we discuss a number of these. The GWP-reference calculation in Section 9 is another special case. Appendix F gives the complete list of the ‘non-standard’ calculations.

12a. WEC Energy Use Scenarios

Since the initial specifications for the calculations (as reproduced in Appendix A) were produced, a new set of emission scenarios have been constructed by the World Energy Council (WEC, 1993). In order to convert these to total industrial carbon releases, as used in the present analyses, a number of modifications have been required. The main changes are the inclusion of ‘non-energy’ contributions from cement production and gas-flaring. The task of converting the WEC energy-related CO₂ emissions into the total industrial releases listed in Table 12.1 was undertaken by Gregg Marland.

Table 12.1 gives the specification of the scenarios where linear interpolation is used for the intermediate times. Figure 12.1 shows these modified emission functions for the three cases. Cases A, B and C correspond respectively to ‘weak’ and ‘strong’ emission reductions and an ‘ecological’ scenario.

Figure 12.2 shows the calculated concentrations using Model W.

Year	A	B	C
1990	6.10	6.10	6.10
1995	6.79	6.45	6.15
2000	7.57	6.83	6.21
2005	8.43	7.22	6.27
2010	9.40	7.85	6.34
2015	10.49	8.09	6.41
2020	11.70	8.57	6.49
2025	12.05	9.04	6.64
2050	15.06	12.39	7.48
2075	14.95	11.82	4.71
2100	16.50	11.68	2.57

Table 12.1. Specification of the World Energy Council scenarios, modified to correspond to the definition of industrial emissions used in the present calculations. Releases are in Gt C y⁻¹, linearly interpolated between the specified years.

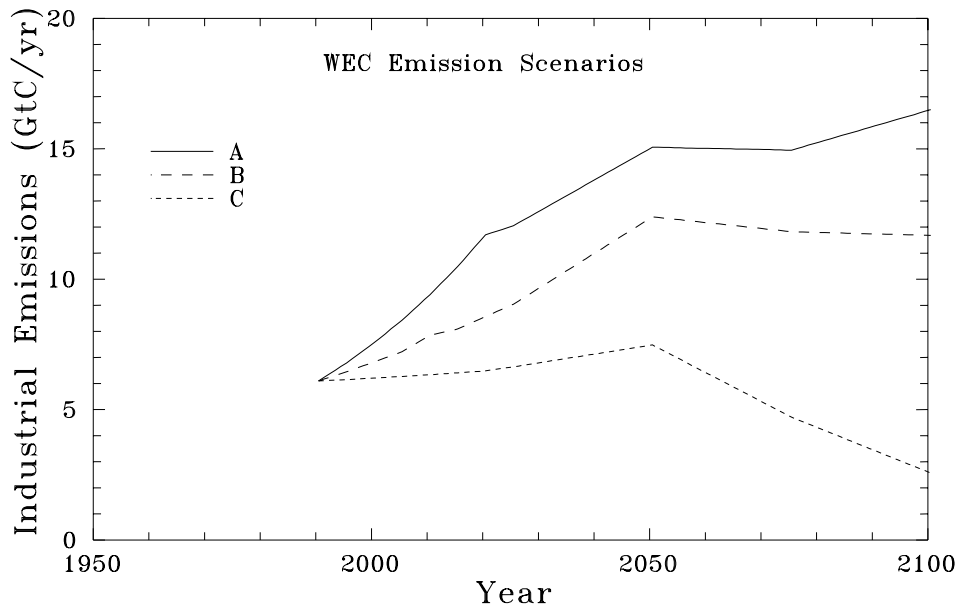


Figure 12.1 World Energy Council CO₂ emission scenarios, converted to total industrial emissions by including cement production and gas flaring.

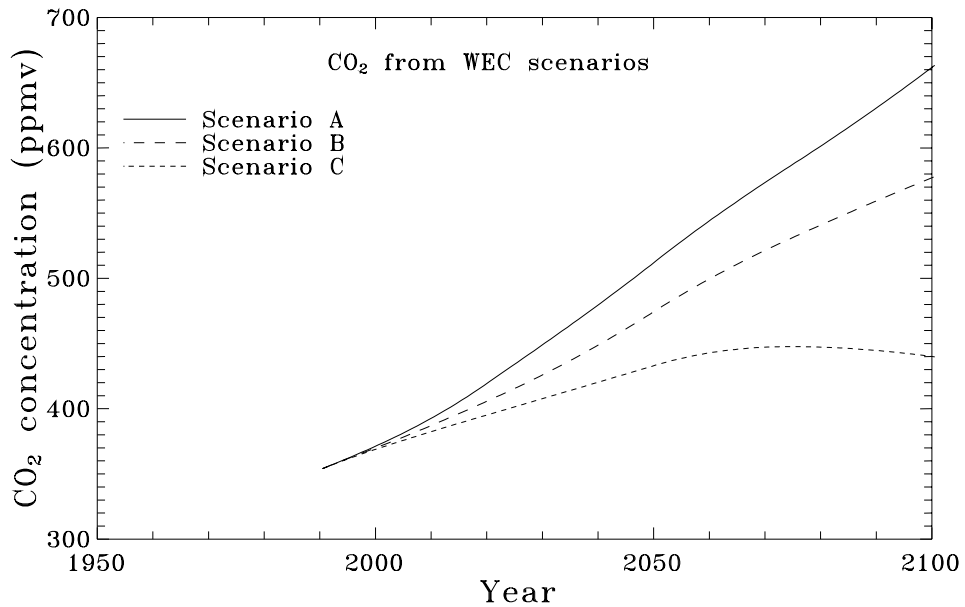


Figure 12.2 CO₂ concentrations calculated using the WEC emission scenarios in Model W.

12b Climate sensitivity

The standard specifications in Appendix A require an absence of any feedback between CO₂ and climate. This restriction does not exclude calculations with a 'CO₂-fertilisation' response which is sometimes referred to as a feedback (e.g. Wigley and Raper, 1992). Enting (1994) proposed the terminology 'carbon-cycle feedback' for discussing fertilisation in feedback terms and 'CO₂-climate' feedback for those processes where the carbon cycle is affected by climate change. In these terms, this section deals with CO₂-climate feedback.

The IPCC reports (IPCC 1990, 1992, 1994) list a variety of potential mechanisms for CO₂-climate feedback. Most of the oceanic feedbacks generally involve changes in ocean circulation. Of the models considered here, only the ocean GCMs could address this question and only if run in 'on-line' mode (as opposed to using previously calculated transport fields). Feedbacks in the terrestrial component can be represented with a range of simple parameterisations. However, because a very large number of processes are of potential importance (e.g. Harvey, 1989b), and because many systems involve sets of competing effects, there are serious difficulties in trying to validate such models.

Many of the terrestrial models included the capability of representing the effects of climate change. However in most such models, this capability was disabled in order to comply with the specifications in Appendix A. The cases in which it was included were the forward runs with IMAGE-2 (denoted R*, c.f. Model R without feedbacks) and all runs with Model T. The various results quoted in the preceding sections indicate that these feedbacks would not play a large role in the future carbon budget. None of the models used here considered the role of climatic change in changing ocean circulation.

12c. Terrestrial modelling

The instructions in Appendix A provide that the effects of land-use change shall be specified in terms of the net flux. Thus, modelling the carbon changes associated with changes in land use is regarded as being external to the model calculations required here. We are specifying the use of a single model for the flux from land-use change: essentially the model of Houghton et al. (1983).

The specification of net fluxes is appropriate for the objectives of the IPCC exercise, since it is the net flux that is the anthropogenic forcing. However in spite of its simplicity, the net flux may not be the most natural description in terms of model representations. As noted in Appendix A, models with a first-order loss rate in carbon reservoirs will tend to 'recover' from prescribed perturbations so that the perturbing flux is not identical to the net flux (see also Enting and Lassey, 1993).

In the various versions of Model B, the processes of land-use change were modelled internally in terms of a prescribed harvesting rate which was adjusted to approximately reproduce the

prescribed net fluxes. The significance of this difference can not be readily assessed because of the other significant difference in the various versions of Model B — the non-zero residual flux extrapolated into the future as a constant.

Model R (and R*) also included internal modelling of terrestrial changes associated with land-use change, even though (in Model R) no climatic feedbacks were included after 1990. The model predicted flux variations through the 21st century that translated into irregular variations in the industrial emissions that were deduced from atmospheric balance when following the prescribed smooth concentration profiles. In particular there were two periods of significant regrowth —around 2050 and 2100.

Refined terrestrial modelling is likely to be an important part of future model development. A more flexible approach to the modelling of the flux from land-use change should allow a more incisive assessment of the uncertainties inherent in this component of the carbon budget. As well as a need for more sophisticated modelling, there is a need for standardised descriptions so that different modelling approaches can be meaningfully compared.

12d. Pathways to stabilisation

In order to be able to compare the results from the different models, the stabilisation calculations specified a prescribed set of concentration profiles (Figure 8.1) defining the way in which stabilisation was to be achieved. The main principle guiding the choice of these profiles is that the implied emissions should not be required to change too abruptly, and certainly not discontinuously. This implies that the specified concentration profiles should have continuous first derivatives.

This still leaves considerable ambiguity in how the profiles should be defined. As emphasised in the introduction, it is not the role of the IPCC Working Group 1, (and certainly not the role of this report) to recommend specific policy options. However, there are a few general points that can be made:

- Delaying reductions in emissions does not greatly change the total emissions that are consistent with achieving stabilisation of CO₂ concentrations.
- The main penalties for delay are firstly, the need to make reductions more rapidly at some time in the future and secondly, the fact that the reductions will be relative to the ‘low-emission’ situation required towards the end of next century. Increased costs are to be expected for both more rapid reductions and a greater marginal cost when decreasing emissions from a low level as compared to decreasing them from a high level.
- The requirements of the Framework Convention on Climate Change impose a complex set of criteria on pathways to stabilisation:
 - A restriction on climate change, presumably implying a stabilisation of concentrations;

- A restriction on rate of climate change, presumably related in part to rates of change of greenhouse gas concentrations;
- A need to avoid adverse economic consequences of low emission requirements;
- A need to avoid adverse economic consequences of rapid decreases in emission rates.

Several of the model calculations contributed did not follow the specified profiles. These have been noted earlier; see also Appendix F.

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13. Conclusions

The calculations in the report were produced as input to the carbon cycle chapters of the reports of Working Group 1 of the Intergovernmental Panel on Climate Change (IPCC, 1994, 1995). Those reports summarise the results presented here. However, in concluding this report we can take a somewhat wider view, and review the exercise in terms of five main questions that need to be addressed:

- What are the most important specific results and generalisations?
- How reliable are these results?
- How reliable is this type of modelling?
- What are the main reasons for uncertainty?
- How can future modelling be improved?

- The most important specific results are:
 - Continuing increases in fossil carbon emissions will lead to continuing increases in atmospheric CO₂.
 - Even stabilising emissions at 1995 levels will lead to increasing CO₂ concentrations.
 - Therefore, major reductions in CO₂ emissions are required in order to stabilise atmospheric CO₂ levels.
 - We have emphasised the case of stabilisation at 650 ppmv because this is typical of levels used in atmospheric GCMs in ‘CO₂-doubling’ experiments — i.e., 650 ppmv is approximately double the 1970s levels often used for 1 × CO₂ experiments so that the models can be checked against recent climatic data. To stabilise at this level via our suggested profile requires that the rate of increase in emissions decrease at once, peak at between 8 to 12 Gt C y⁻¹ around the end of the 21st century, and decline steadily over the 22nd century as the stabilisation level is approached. Maintaining concentrations at 650 ppmv will require further reductions thereafter.

- The main contribution to the uncertainty in the present modelling exercise comes from uncertainties in the current carbon budget. Of these the most important is the current net flux from land-use change. There are additional uncertainties arising from the modelling prescription — the exclusion of feedbacks and the assumption of no ‘residual sink’ forcing CO₂-fertilisation to be set to balance the budget. Section 12 reported results that went beyond our specifications to explore these issues. Although only a small number of cases were treated, the results suggest that the restrictions that were imposed in Appendix A have not greatly limited the applicability of the results.

As noted in the introduction, the concentration profiles shown in Figure 8.1 are in no way intended as recommendations for specific action. When actions are proposed under

the Framework Convention on Climate Change, specific calculations will be required and it will be models like those used here that will be available for such calculations. The results presented here indicate that such calculations will be adequate as an initial guide to action but that strategies for achieving concentration targets will have to be defined in an adaptable form that evolves as knowledge improves.

- The scope for improvement in modelling is through better modelling and refinements in techniques for evaluating and validating models. Some particular needs are:
 - Greater effort devoted to the development and validation of models of terrestrial carbon exchanges.
 - The reasons for differences in the transport of the ocean GCMs need to be identified and the models refined. The World Ocean Circulation Experiment should contribute significantly to this.
 - There is a need for more mechanistic models that can directly represent processes that lead to climatic feedbacks.
 - Even without improvement in models, the reliability of modelling can be expected to improve as longer data records become available with the passage of time.

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For the electronic edition, all references have been left in the form given in the print edition, but where updated information is available, it has been added [in brackets].

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Appendix A: Instructions for Calculations

This appendix reproduces the instructions that were prepared for the calculations by T. Wigley and I. Enting. Draft versions of these instructions were circulated to potential participants (and other interested parties) by the co-ordinators. A final version was circulated from the IPCC Working Group 1 secretariat at Bracknell. For the purposes of this appendix, the various sections of the instructions have been re-numbered by a prefix 'A.', in order to avoid ambiguity. A number of minor typographical errors have been corrected. Other points at which revision or clarification has proved necessary are flagged with footnotes. Contact addresses have been deleted.

Carbon Cycle Model Calculations for the IPCC

Working Group 1 of IPCC is seeking calculations relating future atmospheric CO₂ concentrations to emissions, particularly for cases involving possible stabilization of concentrations¹. At a joint meeting of the IPCC WG1 Bureau and the Chairs of the International Ozone Assessment Panel (Bath, U.K., 18–19 February 1993) Tom Wigley and Ian Enting were charged with the responsibility of convening and coordinating this activity. We are seeking participation from carbon cycle modelling groups world-wide.

The primary task of WG1 in this context is to provide illustrative emissions pathways that lead to concentration stabilization.

Contents

- A.1:** Summary of calculations required.
- A.2:** Deliverables.
- A.3:** Background.
- A.4:** Data sets prescribed.
- A.5:** Reporting and model comparison process.
- A.6:** Technical notes:
 - A.6.A:** Land-use emissions prior to 1850.
 - A.6.B:** Net flux vs. gross flux from deforestation.
 - A.6.C:** Avoiding emission discontinuities.
 - A.6.D:** Iterative inverse calculations.
 - A.6.E:** Details of IS92a–f.
 - A.6.F:** Other aspects of the scenarios.

¹The calculations are required for the IPCC report on *Radiative Forcing of Climate Change*.

(Contact addresses deleted)

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A.1. Summary of calculations required.

A.1a. General

The calculations required are integrations of global carbon cycle models from pre-industrial times (starting at 1765) to 2100 or preferably to 2200. There are two aspects to the exercise: (a) an assessment of the uncertainty due to uncertainties regarding the current carbon budget; (b) an assessment of the uncertainties arising from differences between models. In order to separate these effects, we propose a set of standard conditions to explore inter-model differences and then a series of sensitivity studies to explore the consequences of current uncertainties in the carbon cycle.

A.1b. Standard integrations

The calculations have been grouped in order of importance since the full set of ‘interesting’ cases is larger than many groups will want to undertake. The **bold face** 4 or 5 character abbreviations are used throughout our description to distinguish cases. The annotation ‘forward’ or ‘inverse’ refers to the period from 1990 onward. For the inverse calculations we provide specified concentration histories ¹. For the forward calculations the sources are specified. The choice between inverse and forward treatment of the period 1765 to 1990 is left open. A specified concentration history for 1765 to 1990 is provided for use in inverse calculations and for fitting to (as well as possible) in forward calculations. Technical Note A.6.D notes some relevant aspects of inverse calculations.

Essential

i: Stabilization at 650ppmv. Deduce industrial ² emissions. *inverse* **S650**

ii: Stabilization at 450ppmv. Deduce industrial emissions. *inverse* **S450**

Highly desirable

¹The current ‘IPCC-preferred’ terminology is ‘profile’ for such functions of time, with the term ‘scenario’ reserved for cases based on full policy-oriented analysis.

²The term ‘industrial’ refers to production, rather than the end-use sector. Our usage follows IPCC(1990, 1992). Current usage is generally to avoid ‘industrial’ as being ambiguous.

iii, iv: Impulse response function (as input to GWP calculations). Calculated relative to pre-industrial state and as perturbation to S650. *forward* **Iinit** and **Ipert**

v: IS92a. *forward* **IS92a**

vi: IS92a to 2000 then constant industrial emissions. *forward* **DEC0%**

vii: IS92a to 2000 then industrial emissions decreasing at 1% per year. *forward* **DEC1%**

viii: Stabilization at 350ppmv. Deduce industrial emissions. *inverse* **S350**

Desirable

ix: Stabilization at 550ppmv ¹ with delayed implementation. Deduce industrial emissions. *inverse* **DS550**

x: Stabilization at 450ppmv with delayed implementation. Deduce industrial emissions. *inverse* **DS450**

xi – xii: IS92c, IS92f. (The extreme cases ²). *forward* **IS92c** and **IS92f**

Possibly useful

xiii: Stabilization at 750ppmv. Deduce industrial emissions. *inverse* **S750**

xiv: Stabilization at 550ppmv. Deduce industrial emissions. *inverse* **S550**

xv: IS92a to 2000 then industrial emissions decreasing at 2% per year. *forward* **DEC2%**

xvi – xviii: IS92b, d, e. *forward* **IS92b IS92d IS92e**

A.1c. Specifications for standard cases

- From 1990 onwards, all standard cases use specified net flux from land-use change, calculate any fluxes from CO₂ fertilization and, depending on which case is considered, either deduce industrial emissions ³ from specified concentrations (*inverse*) or calculate concentrations from specified industrial emissions (*forward*).
- The future net flux from land-use change is described in Note A.6.E. Forward integrations of the IS92a–f industrial sources should use the IPCC 1992 deforestation scenarios for 2000 to 2100 as given. All other cases should use the modified IS92a (i.e. IS92a* from Table 4 of Note A.6.E) which goes to zero at 2100 and remains zero. All cases should use linear interpolation over 1990 to 2000 to connect the land-use flux used in the initialization phase with whichever case is used after 2000.

¹Early versions of the instructions referred to a non-existent DS650 case at this point.

²This is an error. The upper extreme is IS92e, not IS92f, and so IS92e is used in the comparisons in other sections of this report

³For the purposes of the Framework Convention on Climate Change, an analysis in terms of total anthropogenic source would be more suitable. See Section 3.

- For the effect of land-use change pre-1990, the net flux from Houghton is provided as an option (Note A.6.A). If some alternative is used then the net flux from land-use change should be 1.6 Gt C y^{-1} averaged over 1980–89 inclusive (except in the sensitivity studies). This is the IPCC (1990) ‘best guess’ value and is close to the estimates by Houghton.
- The atmospheric CO_2 concentration should agree as well as possible with the supplied fit to the observational record. If the period 1765 to 1990 is treated with inverse modelling, then the supplied concentration record should be used.
- The rate of increase of atmospheric CO_2 should be fixed at 1.7 ppmv y^{-1} for mid-1990 (i.e. $t = 1990.5$), except in sensitivity studies. (See Note A.6.C). For inverse calculations from 1990 onwards (i.e. the stabilization cases), the 1990 concentration needs to be fixed at the starting value of the prescribed time series. We specify 354.17 ppmv for mid-1990.
- The calculation of the impulse response should be as a perturbation from pre-industrial equilibrium with concentration 278 ppmv (with perturbation from S650 as an optional extra). The input should be 10 Gt C over 1 year. For the perturbation case, the 10 Gt should be released during 1995. The integrations should be for 200 years or preferably 500.
- Recommended constants: $1 \text{ ppmv} = 2.123 \text{ Gt C}$ in atmosphere; ocean area = $3.62 \times 10^{14} \text{ m}^2$.

A.1d. Output

Essential

- i:** Fossil carbon emissions (in gigatonnes per year) and CO_2 concentrations (in ppmv) for each case considered, for the period 1765 to 2100.
- ii:** Contents of terrestrial biosphere reservoirs (annual data in Gt C) and fluxes between reservoirs (in Gt C y^{-1}), especially atmosphere-to-ocean and atmosphere-to-terrestrial-biosphere.

Desirable

- iii:** Mixed layer ^{14}C , as $\Delta^{14}\text{C}$ in ‰.
- iv:** Ocean ^{14}C inventory for 1/1/74 and preferably over the period 1940–1990. Given as excess ^{14}C atoms per square meter.
- v:** Results as described above extended to 2200 or beyond.

Further details are given in Section A.2.

A.1e. Sensitivity studies

Modellers will perform such sensitivity calculations as they judge necessary. Our suggestions of standard cases for intercomparisons are:

- i:** Explore sensitivity to fixing the rate of concentration increase to the mid-1990 value of 1.7 ppmv y⁻¹.
- ii:** Explore sensitivity to fixing net flux from land-use change at an average of 1.6 Gt C y⁻¹ over 1980–90. We suggest using 0.6 and 2.6 Gt C y⁻¹.
- iii:** Compare calculations with two different forms of CO₂-enhanced production:
(a): Growth logarithmic $\propto [1 + \beta \ln(C/C_0)]$, (b): Saturation $\propto G_\infty \frac{C-C_c}{C+b}$ with $C_c = 80$ ppmv and the constraint $G_\infty = (C_0 + b)/(C_0 - C_c)$ and b used for tuning.
(see Allen et al. *Global Biogeochemical Cycles*, 1, p1).

A.1f. Data provided ¹

- i:** $C(t)$ 1765 to 1990. For input to inverse calculations and fitting in forward cases.
- ii:** $C(t)$ for 1990 to 2200 for the stabilization cases. (7 cases)
- iii:** Fossil carbon emissions for 1844–1990.
- iv:** Atmospheric ¹⁴C for 1800 to 1990 for cases with ¹⁴C forced to track atmospheric levels.
- v:** Net release from land-use change, $D_n(t)$ from Houghton.

Time series (i) and (ii) are provided in two versions, one for beginning of year values and one for mid-year values. We also provide alternative versions of these time series with mid-1990 gradients of 1.6 and 1.8 ppmv for use in the sensitivity studies.

A.2. Deliverables

The most important outputs are the emissions (for the inverse calculations) and the concentrations (for the forward calculations). The simplest way to provide these data is as annual $E(t)$ and $C(t)$ time series over the full period of the analysis (1765 to the chosen end date). Emissions data must be broken down into industrial and net land-use emissions.

To aid in the interpretation of the results (inter-model differences), other output items are desirable. In particular, 1765-to-end-year annual time series of total terrestrial biomass and flux into

¹Footnote to electronic edition : see Appendix B for details.

the ocean will allow the full budget, and its changes, to be assessed for each model. A breakdown of terrestrial biomass changes into components (above-ground living biomass, litter, soil carbon, etc.) is also desirable, as are gross fluxes, if possible.

We recommend the following file format for ASCII files of time series:

Line 1: Integers N and M

Lines 2 to $N + 1$: Arbitrary identification information.

Lines $N + 2$ to $M + N + 1$: Output records.

The items in the record should be separated by blanks and in floating point format, i.e. suitable for reading by Fortran or Pascal free format reads to real variables. We suggest that the first few items should be

Time As year, with at least one decimal place so that mid-1990 is 1990.5

CO₂ concentration In ppmv, suggest 2 decimal places.

Fossil carbon emissions in Gt C y⁻¹. Suggest at least 2 decimal places.

The ¹⁴C data should be reported as time series with the same file structure as above and the records as

Time As above.

Atmospheric ¹⁴C As $\Delta^{14}\text{C}$ in ‰.

Mixed layer ¹⁴C As $\Delta^{14}\text{C}$ in ‰.

Ocean excess ¹⁴C inventory As excess (above pre-industrial) ¹⁴C atoms per square meter.

The suggested period for ¹⁴C output is 1940 to 1990, expanded to 1765 to 1990 if desired.

Finally, full details should be given of model structure and parameter values used in each run, together with information on how differences between net and gross land-use emissions were accounted for, how the model was initialized, and any other particulars on model structure or modelling strategy that you consider relevant.

A.3. Background

A.3a. The choice of integrations

Working Group 1 of IPCC is seeking calculations of future CO₂ levels, particularly those related to possible stabilization of concentrations. Article 2 of the Climate Convention states that the “ultimate aim” of the Convention is

“... to achieve stabilization of greenhouse gas concentrations ... at a level that would prevent dangerous anthropogenic interference with the climate system ... 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”

The primary task of WG1 in this context is to provide illustrative emissions pathways that lead to concentration stabilization.

At the eighth session of the IPCC (Harare, Zimbabwe, 11–13 November 1992) it was agreed that the deliverables under the 1993–95 workplan of WG1 do not include calculations of the climate implications of the 1992 IPCC emissions scenarios developed by Leggett et al. (1992). Nor will these scenarios be revised ¹. Thus, IPCC WG1 has no remit to pursue the CO₂ concentration implications of the IPCC92 scenarios ². Nevertheless, since such calculations are likely to assist in interpreting the results of stabilization experiments, they are included in the optional part of the present exercise.

In addition, we believe that many modellers will wish to go beyond the basic calculations implied by the requirements of WG1 in other ways. We have listed such additional calculations to try to ensure the maximum degree of comparability between those models for which additional calculations are performed. On the other hand, groups will differ in their capabilities to produce large numbers of calculations. Therefore we have ranked the calculations in order of importance (Section A.1b).

The reasons for including the various additional calculations are as follows:

Additional stabilization cases (S350, S550, S750) These give a more extensive range of options.

The ‘science’ cases (DEC0%, DEC1%, DEC2%) These cases with specified percentage reductions in industrial carbon releases, allow direct comparison of model differences using concentrations from forward calculations. In many contexts, forward calculations are easier to explain.

The ‘delayed’ cases (DS450, DS550 ³) These provide alternative pathways to stabilization that may be more realistic, given the difficulties of achieving stabilization, and at any rate provide cases for assessing the implications of delay.

IS92a–f These provide projections that can be related to specific energy policies as described in the IPCC 1992 WG1 update.

¹However a set of new energy-use scenarios have been calculated by the World Energy Council. These are discussed in Section 12 of this report.

²These scenarios are currently (1994) under review. In the event of their being assessed as inadequate, the specifications would have to be regarded as ‘profiles’ that are of interest for comparison with earlier studies and also to the extent that they span ranges relevant in terms of realistic scenarios

³Early versions of the instructions referred to a non-existent DS650 case at this point.

Impulse response function (Iinit, Ipert) This is required for determining the greenhouse warming potentials (GWP) that characterise the relative importance of the various greenhouse gases.

A.3b. The basis of technical specifications

Our principal requirements are that **models should produce an acceptable fit to the record of CO₂ concentrations over the industrial period, and that models should treat processes in the past and future in an equivalent manner**. We also require that the components of the model's carbon budget should lie within the recognized uncertainties in the observed carbon budget.

There are two different ways that these requirements may be achieved, using either forward or inverse modelling. In the forward modelling approach, input emissions from industrial sources and land-use changes are specified, and model parameters adjusted to achieve an optimum fit between modelled and observed concentrations. In the inverse approach, the model is run so as to match observed concentrations exactly, producing emissions as output. Model parameters are then adjusted to optimize the fit between modelled emissions and independent estimates of these emissions. Modelling groups are free to choose either of these methods (or, if possible, both) for the period 1765 to 1990.

In choosing the modelling strategy modellers should consider

- The fact that the atmospheric CO₂ history is better known than most other components.
- The important role of ¹⁴C in constraining ocean carbon uptake.

A further requirement is that the calculations performed by the various modelling groups be as easy to compare and interpret as possible. To this end, we have imposed certain constraints on the calculations (see Section A.1c) in addition to providing standardized input data sets for past concentrations, past industrial emissions and past net emissions from land-use changes: See Note A.6.A.

Use of land-use emissions data as an input raises two problems, specifying emissions prior to 1850, and accounting for differences between net and gross emissions: see Notes A.6.A and A.6.B.

A.4. Data sets prescribed

All input data will be provided as annual time series on Mac or PC floppy disk. Ian Enting will also be able to send the files by e-mail to any group that supplies an address accessible from

internet. In addition, the data sets are available through the ftp facility described in Section A.5.

Concentration data are smoothed versions of data from ice cores (Neftel et al., 1985; Friedli et al., 1986) and atmospheric observations (MLO data from Keeling, 1991). They begin in 1765, which is the required starting year for all calculations. Industrial emissions are those given by Keeling (1991) and Marland and Boden (1991), linearly extrapolated back to zero in 1844 to avoid a step function start at the beginning of the published record. The additional data for 1990 and revisions for 1985 to 1989 are from Marland (personal communication). Land-use-change emissions are the latest data from R.A. Houghton (1993, personal communication, see also Notes A.6.A and A.6.B). Industrial and land-use emissions data will be supplied on floppy disk as annual values.

Year Decade	0	1	2	3	4	5	6	7	8	9
1850	0.4357	0.4675	0.4824	0.4942	0.5040	0.5122	0.5189	0.5245	0.5296	0.5344
1860	0.5419	0.5336	0.5389	0.5440	0.5491	0.5544	0.5569	0.5604	0.5645	0.5688
1870	0.5718	0.5816	0.5877	0.5915	0.5958	0.6001	0.6049	0.6072	0.6089	0.6102
1880	0.6113	0.6422	0.6563	0.6629	0.6684	0.6728	0.6768	0.6777	0.6793	0.6790
1890	0.6872	0.6844	0.6850	0.6844	0.6833	0.6821	0.6804	0.6795	0.6812	0.6830
1900	0.6862	0.7485	0.7668	0.7817	0.7946	0.8060	0.8170	0.8221	0.8249	0.8270
1910	0.8283	0.7731	0.7572	0.7460	0.7435	0.7338	0.7372	0.7365	0.7360	0.7359
1920	0.7360	0.7846	0.7990	0.8110	0.8166	0.8274	0.8246	0.8243	0.8047	0.7804
1930	0.7747	0.7832	0.7786	0.7736	0.7677	0.7616	0.7674	0.7652	0.7616	0.7571
1940	0.7509	0.7300	0.7231	0.7161	0.7124	0.7094	0.7578	0.7682	0.7740	0.7759
1950	0.7824	0.9463	0.9872	0.9918	1.0885	1.1264	1.1551	1.0907	1.0828	1.0870
1960	1.0854	1.2317	1.2707	1.3092	1.3390	1.3627	1.3327	1.3323	1.3452	1.3500
1970	1.2972	1.2771	1.2459	1.2791	1.2595	1.2554	1.3386	1.3629	1.3628	1.4045
1980	1.4149	1.4351	1.4795	1.5098	1.5674	1.5959	1.6606	1.6942	1.7113	1.7053
1990	1.7129	—	—	—	—	—	—	—	—	—

Table A.1 Revised emissions from land-use change. From Houghton — see papers from IPCC meeting on feedbacks, Woods Hole, October 1992. Annual releases in Gt C.

Year Decade	0	1	2	3	4	5	6	7	8	9
1840	0.000	0.000	0.000	0.000	0.000	0.006	0.012	0.019	0.025	0.031
1850	0.037	0.044	0.050	0.056	0.062	0.068	0.075	0.081	0.087	0.093
1860	0.093	0.099	0.098	0.106	0.115	0.122	0.129	0.138	0.137	0.142
1870	0.145	0.162	0.176	0.188	0.184	0.189	0.192	0.196	0.197	0.208
1880	0.227	0.244	0.263	0.280	0.282	0.276	0.279	0.298	0.322	0.328
1890	0.350	0.365	0.369	0.362	0.377	0.399	0.412	0.432	0.455	0.497
1900	0.525	0.540	0.553	0.606	0.613	0.647	0.696	0.771	0.737	0.769
1910	0.805	0.822	0.866	0.929	0.838	0.831	0.895	0.945	0.932	0.829
1920	0.959	0.828	0.891	1.005	0.989	1.006	1.006	1.097	1.091	1.172
1930	1.077	0.968	0.874	0.919	0.996	1.032	1.146	1.226	1.161	1.233
1940	1.300	1.337	1.334	1.364	1.352	1.204	1.271	1.422	1.517	1.497
1950	1.638	1.775	1.803	1.848	1.871	2.050	2.185	2.278	2.338	2.471
1960	2.586	2.602	2.708	2.855	3.016	3.154	3.314	3.420	3.596	3.809
1970	4.091	4.242	4.409	4.648	4.656	4.629	4.895	5.034	5.082	5.366
1980	5.264	5.129	5.094	5.085	5.243	5.416	5.600	5.698	5.912	6.024
1990	6.097	—	—	—	—	—	—	—	—	—

Table A.2. Industrial emissions, as tabulated in Trends 91, linearly extrapolated pre-1860. For 1985 to 1990 new values are from Marland, personal communication. Annual releases in Gt C.

A.5. Reporting and model comparison process

In order to enhance communication for the exercise we have set up an *anonymous ftp* area at CSIRO¹. This will contain data files, news, utility programs, etc.

To access it, the procedure *with user input typed like this* and **machine prompts in bold** is:

normal prompt *ftp ftp@dar.csiro.au*

ftp> Name: *ftp* or *anonymous*

password Type your e-mail address

ftp> *cd IPCC*

ftp> *ascii*

ftp> *get filename* using actual filenames. This can be repeated as required.

ftp> *quit*

The file 'read.me' contains a list of the files currently in the area, together with a brief description. The file 'news' will contain progress reports.

All participants will be kept informed of progress as this exercise proceeds. There will be an opportunity to discuss results at the Global Change Institute in Snowmass, Colorado (July 18–30, 1993), to which many modellers have been invited. However, the main venue for discussing results will be at a special IPCC Working Group 1 meeting on 18 September, 1993, following the Fourth International CO₂ Conference in Carqueiranne, France.

On the morning of 18 September, representatives of each modelling group will be given an opportunity to present their calculations. Subsequent discussion will focus on areas of disagreement or uncertainty that have emerged from the presentations, with a view to either resolving those issues which can be resolved immediately, or identifying those issues where disagreement or uncertainty remains and which can only be addressed in the longer term. In order to facilitate discussion at this meeting, results will have to undergo at least some preliminary inter-comparison and interpretation prior to the meeting. We are therefore requesting that results be submitted to either or both of the conveners by the end of July at the latest. Results should be provided in microcomputer-readable form (Mac or PC disk). The eventual plan is to publish the main results as a multi-authored paper in a leading journal. Participants are, however, encouraged to publish complete details of their results individually.

An overall assessment of the modelling exercise will form part of the carbon cycle chapter (lead authors D. Schimel, T. Wigley, D. Alves, M. Heimann, U. Siegenthaler, I. Enting²) of the 1995 IPCC WG1 assessment.

A.6. Technical notes:

¹The description of ftp is the current access mode. The original instructions described an earlier form.

²D. Raynaud was added when Uli Siegenthaler became ill.

Technical note A.6.A: Land-use emissions prior to 1850

Since Houghton's published land-use emissions data begin in 1850 (see Table A.1) and since the extrapolated industrial emissions begin in 1844, forward calculations will give constant concentrations over 1765–1843. We can, however, be quite confident that concentration levels increased over this period. While there is weak evidence that some of this increase may have been part of a natural fluctuation, possibly associated with the Little Ice Age, in order to ensure comparability our standard case ignores this possibility.

Since the initial (1850) land-use emissions value is substantially greater than zero, we can also be reasonably sure that land-use emissions were non-zero over 1765–1849. After consultation with Houghton, we have therefore extended the Houghton record back to 1765 by linearly interpolating from 0.2 Gt C y⁻¹ in 1765 to the Houghton value in 1850.

Technical note A.6.B: Net flux vs. gross flux from deforestation

It should be noted that the Houghton data and the IS92a-f 'deforestation' fluxes are net emissions that account for fluxes associated with processes like regrowth. Depending on model structure, required land-use emissions input (or output when run in inverse mode) may be either net or gross emissions. A number of carbon cycle models (including our own) require gross land-use emissions as their required input. With such models, an imposed gross land-use emissions flux leads to additional model-generated fluxes and, hence, to a difference between the model-determined net terrestrial carbon mass change and the input land-use changes, $D_g(t)$. At least part of this difference may be interpreted as effective regrowth. However, being model-dependent, this will not necessarily be consistent with regrowth values that may be derivable from Houghton's primary data sources. Houghton (personal communication) estimates that past gross land-use emissions could be as much as double the net emissions.

Modellers should therefore be cognizant of this net versus gross land-use emissions difference. Groups choosing to employ the forward approach to initialization will have to decide how to handle this difference.

This problem also applies if the inverse approach to initialization is used. In this case, if the model uses gross emissions, a comparison is required between model-derived gross land-use emissions and the Houghton or other net emissions data in order to ensure consistency between modelled and observed data. This could be done by comparing the full (1765–1990) emissions time series in some way. However, to make the results from different modelling groups more directly comparable, we specify the following procedure: Because of the large uncertainties in the record of past land-use emissions, inverse calculations should only be constrained to produce a specific value of the mean net land-use flux over the 1980s (i.e., 1980–1989 inclusive), viz. 1.6 GtC y⁻¹.

Technical note A.6.C: Avoiding emission discontinuities

For ease of interpretation by policy makers, we must ensure that the results have no apparent oddities or characteristics that are unobtainable in terms of practical policies (such as very rapid emissions changes). In particular, we must attempt to ensure that there is no marked emissions discontinuity at the starting year for the main inverse calculations (viz. 1990). To do this requires $\frac{dC}{dt}$ to be continuous in the year 1990. This, in turn, requires $\frac{dC}{dt}$ at the start of each future $C(t)$ scenario to be equal to that at the end of the observational record. For inverse calculations from 1990 onwards, we also need to ensure continuity of C .

Requiring C and $\frac{dC}{dt}$ to be continuous is another reason why a common observational record of $C(t)$ should be used by all modelling groups. The observed value of $\frac{dC}{dt}$ in 1990 from this record has been used as the starting value for the future concentration scenarios. This will lead directly to continuous emissions in 1990 if the inverse modelling approach is used prior to 1990. If the forward approach is used, some form of iterative adjustment will be needed in order to match $\frac{dC}{dt}$ in 1990.

Our standard values for 1990.5 are $C = 354.17$ ppmv and $\frac{dC}{dt} = 1.7$ ppmv y^{-1} . These should be used in all cases except those which explicitly explore the sensitivity to these choices.

Technical note A.6.D: Iterative inverse calculations

Because the primary IPCC interest is in CO₂ stabilization¹, many of the calculations are inverse calculations with input specified in terms of prescribed concentrations. While some models can perform such inverse calculations within the integration procedure, in other cases it will be necessary to use an iterative technique, starting with an approximate source and successively refining it to minimize the differences between calculated and prescribed concentrations. Further information is available from Tom Wigley.

As an alternative to this inversion procedure, those groups who have calculated the impulse response function for use in GWP calculations can use it for inversion calculations using the expressions described by Enting and Mansbridge *Inverse Problems*, 3, L63, (1987). This will need to be applied iteratively in non-linear models. Further information is available from Ian Enting.

Both iterative and direct inverse calculations assume that all model parameters have been prescribed (as might be the case when determining emissions to match a future concentration scenario). For tuning model parameters to optimize the budget when fitting to observed concentrations, either inversion method would have to be embedded in an iterative parameter-tuning loop.

¹E.g., WMO-Executive Council resolution EC-XLIV requesting the IPCC to provide assessments to support the FCCC and in particular related to the objective of stabilization of greenhouse gases...

Technical note A.6.E: Details of IS92a-f

The IPCC 1992 WG1 update does not give a sufficiently complete description of the scenarios for the purposes of these calculations. When this modelling exercise was first proposed in 1992, the IPCC Secretariat circulated additional information which gave greater detail but which contained a few errors and a number of crude approximations to the published information and which had some totals failing to balance due to rounding. Many of those involved in the present exercise will have received this information.

We therefore recommend the use of the values from Table A.4 which incorporates the following aspects:

- We have, to the best of our ability, reconstructed the requisite details in the scenarios described by the IPCC 1992 report. Table A.3 lists our reconstruction.
- The total is expressed as an industrial plus deforestation (i.e. land-use) term as required for our calculations.
- For all cases we recommend that the land-use term be linearly interpolated over 1991-2000 between the 1990 value used in the initialization phase and the 2000 value from Table A.4.
- For the cases using the IS92a–f industrial sources, the corresponding IS92a–f deforestation fluxes from Table A.4 should be used.
- For the other cases (stabilization and fixed percentage reductions) the IS92a* flux from the final column of Table A.3 should be used.
- The values from Table A.4 should be linearly interpolated as required for the period 1991 onwards. (In particular, the 1990 industrial release should be the value from Marland).

Year	Total						Deforest			
	IS92a	IS92b	IS92c	IS92d	IS92e	IS92f	IS92abe	IS92d	IS92f	IS92c
1990	7.4	7.4	7.4	7.3	7.4	7.4	(1.3)	(1.2)	(1.3)	(1.3)
1995	7.9	7.9	7.2	7.3	8.2	8.0	1.3	(1.05)	(1.3)	(1.3)
2000	8.4	8.2	7.5	7.5	9.1	8.8	1.3	0.9	1.3	1.3
2005	9.2	8.8	7.8	7.8	10.2	9.7	1.26	0.78	1.3	1.26
2010	9.9	9.4	8.1	8.2	11.4	10.8	1.22	0.66	1.3	1.22
2015	10.6	10.2	8.3	8.5	12.6	11.9	1.18	0.54	1.3	1.18
2020	11.4	10.9	8.5	8.8	13.7	13.1	1.14	0.42	1.3	1.14
2025	12.2	11.8	8.8	9.3	15.1	14.4	1.1	0.3	1.3	1.1
2050	14.5	13.8	7.5	9.0	20.1	17.2	0.8	0.1	0.9	0.7
2075	16.3	15.4	5.6	9.3	27.0	21.2	0.15	-0.1	0.35	0.0
2100	20.3	19.1	4.6	10.3	35.8	26.6	-0.1	-0.1	0.0	-0.2

Table A.3. Specification of total sources for IS92a–f, based on IPCC 1992 and linear interpolation of deforestation flux. The industrial component should be obtained from linear interpolation of the totals in this table, minus the linearly interpolated deforestation values. The brackets indicate that we recommend linearly interpolating from the ‘deforestation’ value used in the initialization phase.

Year	Industrial						Deforest				
	92a	92b	92c	92d	92e	92f	92abe	92d	92f	92c	92a*
1990	6.10	6.10	6.10	6.10	6.10	6.1	D_0	D_0	D_0	D_0	D_0
1995	6.60	6.60	5.90	6.15	6.90	6.7	(1.3)	(1.05)	(1.3)	(1.3)	(1.3)
2000	7.10	6.90	6.20	6.60	7.80	7.5	1.3	0.9	1.3	1.3	1.3
2005	7.94	7.54	6.54	7.02	8.94	8.4	1.26	0.78	1.3	1.26	1.26
2010	8.68	8.18	6.88	7.54	10.18	9.5	1.22	0.66	1.3	1.22	1.22
2015	9.42	9.02	7.12	7.96	11.42	10.6	1.18	0.54	1.3	1.18	1.18
2020	10.26	9.76	7.36	8.38	12.56	11.8	1.14	0.42	1.3	1.14	1.14
2025	11.10	10.70	7.70	9.00	14.00	13.1	1.1	0.3	1.3	1.1	1.1
2050	13.70	13.00	6.80	8.90	19.30	16.3	0.8	0.1	0.9	0.7	0.8
2075	16.15	15.25	5.70	9.30	26.85	20.85	0.15	-0.1	0.35	0.0	0.15
2100	20.40	19.20	4.80	10.40	35.90	26.60	-0.1	-0.1	0.0	-0.2	0.0
2400	—	—	—	—	—	—	—	—	—	—	0.0

Table A.4. Specification of industrial and deforestation sources for IS92a–f, as recommended for use in these calculations. D_0 indicates that we recommend linearly interpolating from the deforestation value used in the initialization phase. The IS92a* scenario is our recommended net flux from land-use change for all cases except those using the IS92a–f industrial releases. The 1990 industrial source defines the interpolation. The actual 1990 release should be the specified value from Marland.

Technical note A.6.F: Other aspects of the scenarios ¹

The primary calculations are those related to the objectives of the Climate Convention, i.e., concentration stabilization. Since no particular stabilization level has been specified, we must consider a range of possibilities. We could use multiples of the pre-industrial level (e.g., 1.5, 2.0, 2.5 times) or specific ‘round number’ values. The fact that the users of the results (policy advisors and makers) are more likely to ‘understand’ round numbers leads us to choose the latter. The stabilization levels we have chosen are 450 and 650 ppmv (concentration scenarios S450 and S650). Both of these levels would likely require new policies to limit CO₂ emissions. The lower value is probably below the limit of realistic attainability and even the upper value represents a substantial concentration reduction below what might be expected under the central IPCC92 ‘existing policies’ scenario (IS92a).

Higher stabilization levels must correspond to less stringent policies. It is logical, therefore, to require the higher levels to take longer time periods before stabilization is achieved. For ease of interpretation by policy makers, it is essential that stabilization be achieved in a finite time. (This precludes using, for example, an exponential decay towards an asymptotic level. While this might be intellectually appealing to scientists, it would be far less meaningful to the user community.) Stabilization dates cannot be too far into the future, since policy makers would have difficulty interpreting results if significant progress were not apparent by the end of the standard IPCC time horizon (viz. 2100). The stabilization dates we have chosen are: 2100 for the 450 ppmv stabilization level and 2200 for the 650 ppmv level.

There is no simple set of analytical expressions that satisfy all of the above conditions. We have

¹Working Group I has decided to restrict the term ‘scenario’ to cases linked to specific policy choices and to refer to cases defined as mathematical functions as ‘profiles’.

therefore constructed the future $C(t)$ scenarios graphically, modifying our initial projections slightly after running some preliminary inverse calculations to ensure that the output emissions were sensible¹. These $C(t)$ scenarios will be provided as annual values on floppy disk.

Finally, all model runs should span the same time period to ensure intercomparability. We have chosen 1765 as the starting year, since this is the "standard" starting year used in previous IPCC calculations (in particular, the global-mean temperature and sea level projections given in the 1990 IPCC report). For the end point, runs should be carried through at least to the year 2100 and preferably to 2200. Calculations out to 2500 would be useful, since such long runs are more likely to expose inter-model differences. Of course, results become more and more suspect the further one goes into the future. The reason for carrying calculations so far is to aid in the scientific interpretation of the results, not for assisting policy makers.

In addition to the primary future concentration scenarios, we are providing three other scenarios with lower (350 ppmv), intermediate (550 ppmv) and higher (750 ppmv) stabilization levels (scenarios S350, S550 and S750), and two scenarios representing a 20-year delay in initiating the emissions control policy (scenarios DS450 and DS550).

The low, intermediate and high stabilization cases have stabilization dates of 2150, 2150 and 2250. For the low case to lead to an emissions result that is not *a priori* unattainable, this case begins with concentrations increasing, reaching a maximum of around 400 ppmv in 2040 and then declining to reach the final stable level in 2150.

For the delay cases, the first follows the 550 ppmv stabilization path to 2010, and then makes a transition to the lower path to achieve stabilization at 450 ppmv by 2100. The second delay case follows the 650 ppmv stabilization path to 2010, and then makes a transition to achieve stabilization at 550 ppmv by 2150.

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¹To further ensure smoothness, we used Padé approximants (ratios of polynomials in time) to represent the functions between 1990 and the stabilisation point. The 'delayed' cases were represented piecewise using two Padé approximants. Details are given in Appendix B.

Appendix B: Data Sets Provided

Prescribed data files

The following files were made available to participating modellers via internet, as specified in the instructions (Part 5 of Appendix A of this report).

address.txt: Addresses of participants (and some potential participants).

calcs.txt: Summary of instructions, specifying cases and constraints.

calcs.tex: LaTeX source file for the full instructions.

co2spl.dat: Spline fit to Mauna Loa plus ice core data. Standard case, growth rate of 1.7 ppmv/yr for 1990.5. Columns are time, CO₂, d/dt of CO₂. Time intervals 0.5 years 1765.0 to 1990.5

co2-sens.dat: 3 cubic spline fits to Mauna Loa plus ice core data. First is standard case. The other 2 are for sensitivity studies. Growth rates of 1.7, 1.6 and 1.8 ppmv/yr for 1990.5. Columns are time, CO₂, d/dt of CO₂, CO₂, d/dt of CO₂, CO₂, d/dt of CO₂. Time intervals 0.5 years 1765.0 to 1990.5 The curves are plotted in Figures B.1 and B.2.

deforest.dat: Net carbon emissions from land-use change. Annual totals in Gt C. As estimated by R.A. Houghton. Linear extrapolation from 1850 back to 1765. Used for all forward initialisations.

deforest.all: Net carbon flux from land-use change 1765 to 2100. Combination of **deforest.dat** up to 1990 and IS92a modified to go to zero in 2100 and linearly matched to Houghton over 1990 to 2000. Standard series for all stabilisation cases and all cases with fixed percentage reductions in industrial emissions. The data are plotted in Figure B.4.

foss91.dat: Fossil carbon emissions 1765 to 1989. Annual totals in Gt C. From *Trends '91* (CDIAC, 1991), extended back from 1860 as described in instructions.

fossil.dat: Fossil carbon emissions 1765 to 1990. Annual totals in Gt C. From *Trends '91* (CDIAC, 1991), extended back from 1860 as described in instructions. New values for 1985 to 1990 from Marland.

stab.dat: Prescribed CO₂ concentrations for the 7 stabilisation scenarios. Half-year intervals.

c14sth.dat, c14equ.dat, c14nth.dat: Atmospheric ¹⁴C levels for southern hemisphere (extra-tropical), equatorial and northern hemisphere (extra-tropical) regions. Supplied by M. Heimann. These data are plotted in Figure B.5.

Further details

The requirements specified by Wigley and Enting (1993) (i.e., Appendix A of the present report) included the absence of any oddities or characteristics that are unobtainable in terms of practical policies (such as very rapid emissions changes). In particular, they wished to ensure that there is no marked emissions discontinuity at the starting year for the main inverse calculations (viz. 1990). To do this requires $\frac{dC}{dt}$ to be continuous in the year 1990. This, in turn, requires $\frac{dC}{dt}$ at the start of each future $C(t)$ scenario to be equal to that at the end of the observational record.

The standard values for 1990.5 are $C = 354.17$ ppmv and $\frac{dC}{dt} = 1.7$ ppmv y^{-1} . These were prescribed for all cases except those designed for explicit exploration of the sensitivity to these choices.

To ensure smoothness at all times, the pre-1990 and post-1990 segments of the CO₂ history were represented by differentiable functions: smoothing splines pre-1990 and Padé approximants (ratios of polynomials) post-1990.

Past

The CO₂ concentrations for the period 1765 to 1990 were specified as values every six months. These values were a smoothed representation of the combination of direct observations from Mauna Loa (Keeling et al., 1989) and ice-core data from Neftel et al. (1985) and Friedli et al. (1986).

The fits were defined as the functions $f(t)$ that minimised

$$\sum_{j=1}^N [f(t_j) - c_j]^2 / w_j^2 + \lambda \int_{t_1}^{t_N} \left[\frac{d^2}{dt^2} f(t) \right]^2 dt \quad (B.1)$$

where c_j is the observed concentration at time t_j and λ determines the degree of smoothing.

The solution, $f(t)$, is a piecewise cubic polynomial with nodes (discontinuous third derivative) at each data point t_j , i.e., a cubic spline commonly termed a smoothing spline. These approximations have been comprehensively studied. Some of the key results are reviewed by Enting (1987). The main result is that the smoothing spline acts as a low-pass filter with response of $1/[1 + (\omega/\omega_{1/2})^4]$ at frequency ω .

By adjusting the weights, w_j , and/or the smoothing parameter, λ , the degree of smoothing (expressed in terms of $\omega_{1/2}$) can be adjusted.

We have used three differing cases of smoothing to give our preferred reference case (with growth rate of 1.7 ppmv y^{-1}) and two other cases (with growth rates of 1.6 and 1.8 ppmv y^{-1}) for use in the sensitivity studies.

The specifications used for each are:

- Ice-core data with $w_j = 3.0$, Mauna Loa data with $w_j = 0.5$ and $\lambda = 100$ leads to a gradient of 1.7 ppmv y^{-1} at end of the record and $C(1990.5) = 354.17$.
- Tighten fit to Mauna Loa data, using $w_j = 0.29$ but relax fit to 1990 value, using $w_j = 1.74$. This leads to gradient of 1.8 ppmv y^{-1} at end of record and concentration of 354.50.
- Relax fit to Mauna Loa, using $w_j = 1.8$. This leads to a growth rate of 1.6 ppmv y^{-1} and $C(1990.5) = 353.77$.

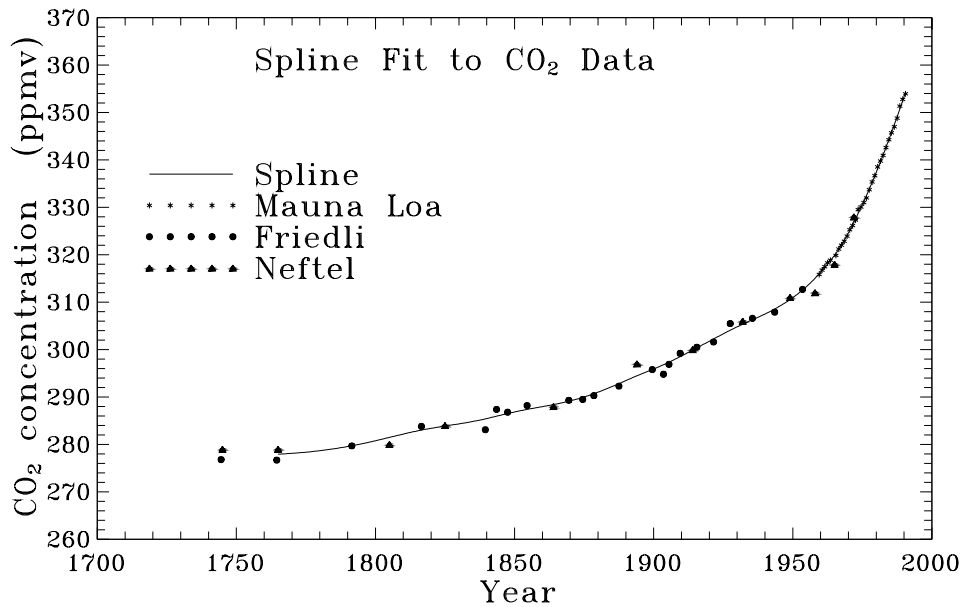


Figure B.1. Spline fit defining prescribed CO₂ concentrations from pre-industrial times to the present, compared to observed concentrations from ice-cores and direct atmospheric measurements.

Figure B.1 shows the preferred spline fit over the period 1765 to 1990. The alternatives are barely distinguishable on this scale. Figure B.2 shows the three splines over the period 1975 to 1990 compared to the data. The question of which curve is the best fit depends on the interpretation that is placed on the CO₂ data. We regard 1988 and 1989 as being anomalously high in CO₂ concentration. The atmospheric $\delta^{13}\text{C}$ for this period is also anomalous (R. Francey, personal communication). The alternative would be to regard 1990 as anomalously low. There is scope for using later data to resolve the question.

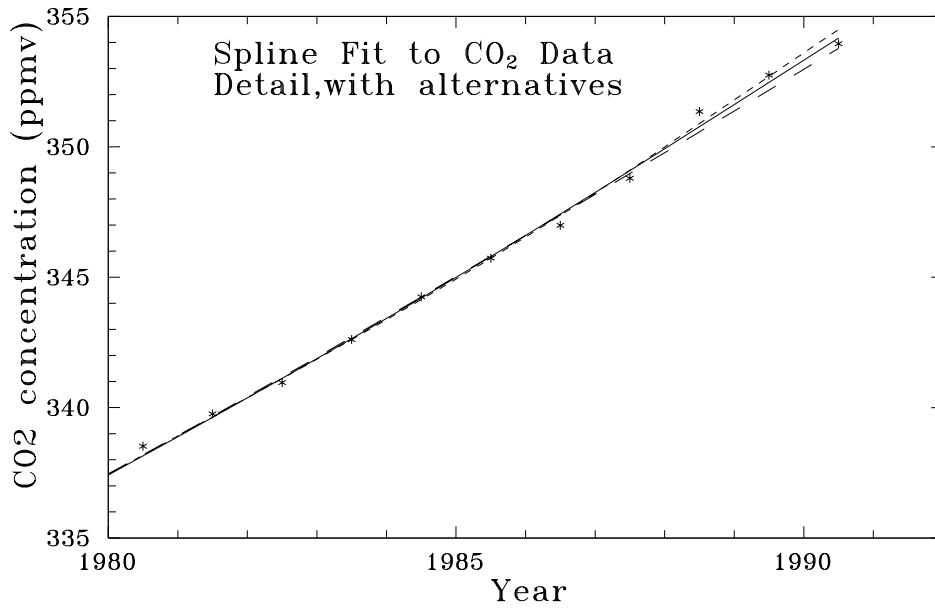


Figure B.2. Prescribed spline fits to CO₂ data showing detail of the period immediately prior to 1990. The standard case is the solid line. The other cases are those defined for sensitivity studies.

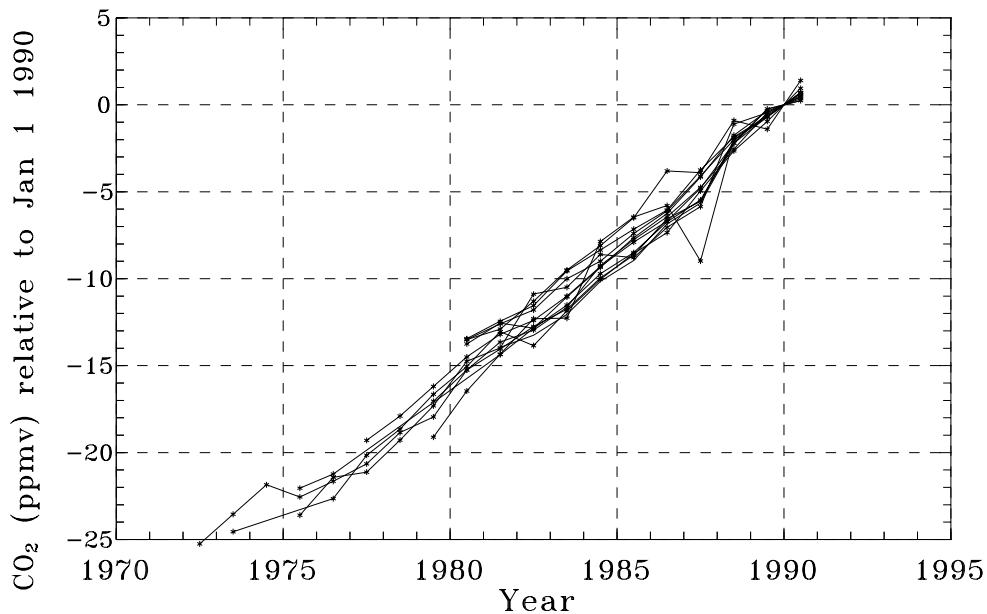


Figure B.3. Growth in atmospheric CO₂ over the 1980s. Annual means of data from CDIAC (1991), normalised to 1989–90 mean.

In view of the importance of the rate of growth in atmospheric CO₂, we show additional data to justify our use of the Mauna Loa record for defining the specified atmospheric CO₂ concentration prior to 1990. Figure B.3 shows data from CDIAC (1991) demonstrating the rate of

increase over the 1980s. The data plotted are annual means, normalised to a common 1989–90 mean of zero. It will be seen that the range 1.6 ± 0.1 ppmv y^{-1} is representative of this data set which includes all stations for which data were available over all or most of the decade. As noted in Section 3, a more recent analysis by the NOAA group suggests 1.53 ppmv y^{-1} as the best estimate of the mean rate of increase over the 1980s. The NOAA estimate effectively weights the data set to take account of the fact that tropical sites are under-represented (as a proportion of the earth’s area) in the NOAA network.

Future

For the ‘stabilisation’ cases, we required a smoothly changing set of values with a regular progression between cases. In order to achieve this, Wigley and Enting began with a set of plausible but ad hoc concentration histories and refined them, firstly by an iterative adjustment to remove rapid changes in the releases and then finally by fitting the curves with smooth functions.

The functions chosen to represent the concentration were Padé approximants, i.e. the ratios of polynomials in time. These were specified as

$$C(x) = \frac{a + bx + cx^2 + dx^3}{1 + ex + fx^2} \quad (B.2)$$

with

$$x = \frac{t - t_0}{t_s - t_0} \quad (B.3)$$

where $t_0 = 1990$ (except in the delayed cases) and t_s is the time of stabilisation.

Three distinct cases were used:

- The basic case, with $d = 0$, had the approximants fitted to specified values at $x = 0$, $x = 1$ and at one other x value ($t = t'$ in Table B.1), together with the constraints in the gradients at $x = 0$ (to match observations) and $x = 1$ (zero gradient).
- The ‘overshoot’ case was specified from values and trends at $x = 0$ and $x = 1$ and the value and trend of zero at a specified time where the concentration peaks. This was only used for S350.
- The delayed cases. These use two approximants to represent the concentrations over the periods 1990–2010 and 2010 to stabilisation. The 1990 to 2010 approximant is one of the basic cases. The second approximant has $t_0 = 2010$ and takes the value and gradient from the first approximant.

	S350	S450	S550	S650	S750	DS450	DS550
t_0	1990.5	1990.5	1990.5	1990.5	1990.5	2011	2011
$c(t_0)$	354.17	354.17	354.17	354.17	354.17	$c_{S550}(2011)$	$c_{S650}(2011)$
$d(t_0)$	1.7	1.7	1.7	1.7	1.7	$d_{S550}(2011)$	$d_{S650}(2011)$
t_s	2150.5	2100.5	2150.5	2200.5	2250.5	2100.5	2150.5
$c(t_s)$	350	450	550	650	750	450	550
$d(t_s)$	0	0	0	0	0	0	0
t'	—	2031	2031	2031	2051	2051	2061
$c(t')$	—	411.91	420.78	429.23	489.17	436.28	474.70
t_m	2041	—	—	—	—	—	—
$c(t_m)$	396.5	—	—	—	—	—	—
$d(t_m)$	0	—	—	—	—	—	—

Table B.1. Specification of Padé approximants used to define the CO₂ concentration histories prior to stabilisation. Here $c(t)$ is the concentration and $d(t)$ is the trend.

The curves defined in this way are plotted in Figure 8.1.

For the future net flux from land-use change, we used a modification of that from IS92a, as described in Appendix A. Figure B.4 shows this specified flux for the future and the specified land-use flux for the past, based on the work of R.A. Houghton.

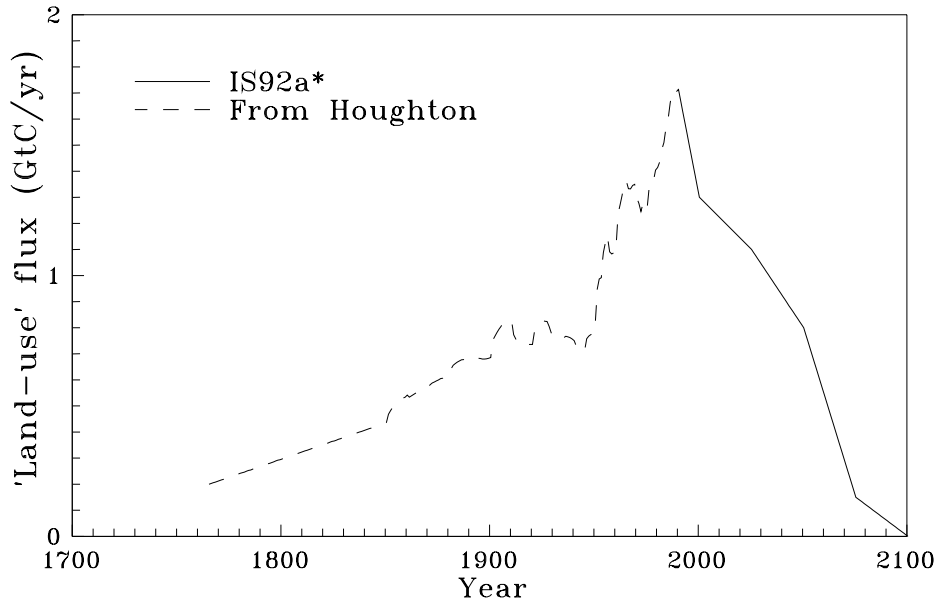


Figure B.4. Prescribed net carbon flux from 'land-use' changes.

Radiocarbon data for validation

Figure B.5 shows the ^{14}C data set provided for model validation studies.

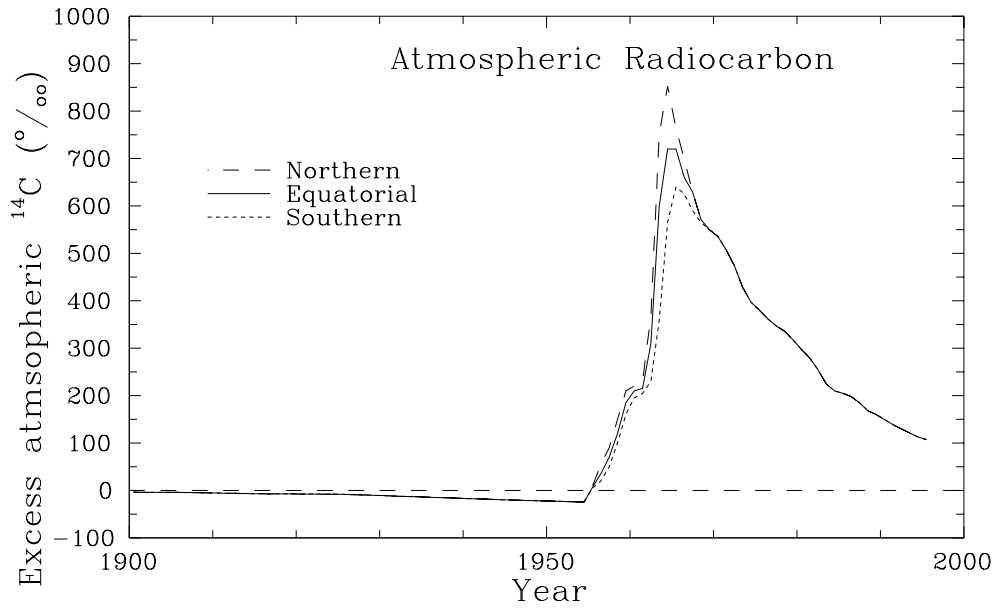


Figure B.5. Atmospheric ^{14}C levels prescribed for validation calculations.

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Appendix C: Descriptions of Models

The following table lists the models for which calculations were contributed.

Code	Authors	Institution
A	Taylor et al.	Aust. National University
B	Emanuel	Oak Ridge Nat. Lab
C	Cohen	UN Economic Commission for Europe
E	Enting and Lassey	CSIRO (DAR) and NIWA
F	Friedlingstein	Belgian Inst. Space Aeronomy
G	Goldstein and Keller	Electric Power Res. Inst, Palo Alto, CA
H	Heimann et al.	Max Planck Inst. fur Meteorol., Hamburg
J	Joos and Siegenthaler	University of Bern
L	Jain and Wuebbles	Lawrence Livermore Nat. Lab.
M	Moore and Braswell	U. New Hampshire
O	Orr and Monfray	Saclay
P	Peng	Oak Ridge Nat. Lab
Q	Le Quéré et al.	Princeton University
R, R*	Alcomó and Krol	RIVM, Netherlands
T	Harvey	U. Toronto
V	Viecelli	Lawrence Livermore Nat. Lab.
W	Wigley	OIES, UCAR, Boulder, CO, USA
Z	Zakharova and Selyakov	State Hydrol. Inst. St. Petersburg

Table C.1. List of models with participating institutions. The code letter is used to identify the models in tables, figures and discussion, in some cases with a subscript to distinguish variants.

Note on electronic edition: the affiliations, contact addresses and e-mail addresses have not been updated for the electronic edition.

Model A

Name: ANU Biosphere/Atmosphere Exchange model (ANU-BACE)

Modellers: J. Taylor[†], J. Lloyd[‡] and G. Farquhar[‡]

Institutions: Centre for Resource and Environmental Studies[†] and
Environmental Biology Group, Research School of Biological Sciences[‡].

(both at) Aust. National University, Canberra, ACT, Australia

Contact: taylorj@cres1.anu.edu.au, jon@rsbs13.anu.edu.au, gdf@rsbs13.anu.edu.au

Summary:

Ocean: Box-diffusion model from Siegenthaler and Oeschger (1987).

Terrestrial: The terrestrial component was represented by 14 different ecosystem types in 10 regions, using the subdivisions and land areas of Houghton et al. (1983). Net primary production was modelled by an equation similar to that used in modern plant growth analysis (Masle et al., 1990):

$$\text{NPP}(t) = \text{GPP}(t)[1 - \phi_0] - mM(t)$$

where M is the biomass, ϕ is the proportion of photosynthesis lost in respiration, and $M(t_0)$ and $\text{NPP}(t_0)$ are tuned to reproduce the present-day biosphere. GPP is the Gross Primary Productivity (photosynthesis) and m is the maintenance respiration coefficient. Mechanistic equations (Farquhar et al., 1980) were used to model the response of GPP and hence NPP to changes in CO_2 . Flow of carbon through the ecosystems was modelled in a similar manner to Taylor and Lloyd (1992).

Calibration: Pre-industrial masses were tuned to give prescribed concentration and rate of change of atmospheric CO_2 in 1990.

Documentation: Farquhar et al. (1993), Masle et al. (1990), Farquhar et al. (1980), Badger (1992), Taylor and Lloyd (1992), Siegenthaler and Oeschger (1987), Lloyd and Farquhar (1995).

Versions run: Two different initialisations were used: forward initialisations for the concentration projections and inverse initialisations for the stabilisation calculations.

Model B

Modeller: W.R. Emanuel

Institution: Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

Present address: University of Virginia/Clark Hall

Charlottesville, Virginia 22903, USA.

Contact wre6s@virginia.edu

Summary:

Ocean: Box diffusion model, $K = 7685 \text{ m}^2/\text{y}$ to match distribution of bomb- ^{14}C . Carbon chemistry is taken from Takahashi (1980).

Terrestrial: 26 ecosystems, each characterised by a distribution of carbon densities for vegetation, litter and soil. Estimates of NPP, standing stocks of carbon in vegetation, litter and soil and recovery times are from the regional studies summarised by Houghton et al. (1987). The rates of transfer into the soil compartments are those generally assumed for the ecosystems involved. All other parameters are from Houghton et al. (1983). Rather than use the prescribed net fluxes for land-use terms, the model was forced using harvesting rates chosen to match those underlying the prescribed net 'land-use' fluxes.

CO₂-fertilisation. The NPP is taken as linear in atmospheric CO₂ content but limited by a logistic dependence on carbon density in the 'vegetation' compartment.

Initialisation: This model was not directly comparable with the main part of the exercise because of an unidentified residual flux. This was determined by an inverse calculation from the specified CO₂ record.

Documentation: Box diffusion model: Oeschger et al. (1975). Terrestrial model: Emanuel et al. (1993).

Cases run: Three variations were run:

- (i) Prescribed land-use term as the net biotic flux (no fertilisation term).
- (ii) Modelled land-use fluxes from harvesting rates (no fertilisation).
- (iii) Modelled land-use fluxes from harvesting rates with fertilisation given by linear increase ($\beta = 0.5$) in production combined with a logistic function limit on maximum carbon density.

Model C

Description: Empirical total response function.

Modeller: B. Cohen

Institution: United Nations Economic Commission for Europe, Palais des Nations, Geneva, Switzerland.

Summary:

The calculations were performed using a parameterisation of the total ‘ocean plus biota’ response which is estimated by fitting the model to historical data.

The model is presented in a finite difference form, corresponding to the differential equation:

$$\frac{d}{dt}C(t) = 0.471m_2Q_{\text{foss}}(t) - m_3C(t) \quad (C.C.1)$$

with m_3 fixed at 0.001 to represent variations on millennial time scales and m_2 fitted by a regression fit of ice-core CO₂ data to fossil fuel releases. Cohen (1992) estimated $m_2 = 0.561$ for his standard case. The factor 0.471 converts GtC to ppmv.

Documentation: Cohen (1992), Cohen and Collette (1991).

Editorial note: This model was not sufficiently consistent with the specifications in Appendix A for us to be able to make use of the results. In particular, the neglect of the terrestrial source was inconsistent with the specifications. It should also be noted that in the period prior to significant industrial emissions the model would imply a decrease of about 25 to 30 ppmv per century, a gross discrepancy from data obtained from ice cores.

Modeller’s response:

The regression corresponding to the specification allows for an intercept term; also $C(t)$ is lagged by one year. A defence of this specification is found in Cohen (1992). It should be noted in particular that an intercept term k is included to account for a slow upward drift in CO₂ concentrations from non-anthropogenic sources. The *a priori* expectation of the sign of the coefficient of the intercept would then be positive and slightly more than offset the decrement in concentrations owing to seepage ($m_3C(t-1)$) in 1850, the initial year of the period fitted. This seems to be the essential point raised above.

To remedy this flaw, the regression was re-estimated with a restriction placed on k . For a value of $k = 0.200$ the initial year increase was 0.100 ppmv corresponding closely to the Siple record for the mid-eighteenth to mid-nineteenth century.

This gives an equilibrium at 550 ppmv with emissions at a rate of 1.5 GtC, compared to 2.1 GtC for Cohen (1992). This is another way of expressing the uncertainties inherent in the regression method of approaching the question of equilibrium pairings of emissions and concentrations.

Model E

Description: Modified box-diffusion model with 2-box terrestrial biota.

Modellers: I.G. Enting[†] and K. R Lassey[‡].

Institutions:

[†] Cooperative Research Centre for Southern Hemisphere Meteorology: CSIRO, Division of Atmospheric Research, Private Bag 1. Mordialloc, Vic 3195 Australia and

[‡] National Institute of Water and Atmospheric Research, P.O. Box 31–311, Lower Hutt, New Zealand.

Contact: ige@dar.csiro.au and srgikrl@grace.cri.nz

Summary:

Ocean: Ocean is conventional box-diffusion model (Oeschger et al., 1975) with the addition of detrital fluxes. (These act to modify the response to isotopic perturbations in the oceans.)

Terrestrial: A 2-box representation is used for the terrestrial biota. Fertilisation uses a hyperbolic response that saturates at $2.4 \times$ initial NPP (for infinite CO_2) (based on Allen et al., 1987). This is applied to a fraction of the terrestrial biota. The fertilisation flux is tuned in the calibration by adjusting this fraction.

Initialisation: All runs are in forward mode pre-1990. Agreement with CO_2 record is achieved by a weighted pointwise least-squares fit to data, as part of the calibration.

Other: The atmosphere is divided into separate tropospheric and stratospheric reservoirs to allow better representation of bomb- ^{14}C . Other special features are: Bayesian calibration approach; ^{14}C forcing from estimated inputs; ocean detrital fluxes.

Calibration: Bayesian calibration approach (Enting and Pearman, 1983, 1986, 1987). Model parameters adjusted to fit selection of: CO_2 concentrations from atmosphere and ice-cores, atmospheric ^{14}C , Suess effect (as determined from tree-rings), ocean ^{14}C . Data items (and prior estimates of parameters) are weighted.

A new calibration was performed for the present study, because new estimates of D_n were used:

- Data sets and adjustable parameter sets as per Enting and Lassey (1993), except that the weightings of the last two CO_2 concentrations are adjusted to force agreement with the prescribed concentration and growth rate for 1990. Land-use and industrial forcings pre-1990 are as specified in Appendix A. Of the cases considered by Enting and Lassey (1993), their ‘low clearing’ cases is the closest to that used here.

Documentation: The model, some results for IS92a–f and sensitivity calculations are documented in CSIRO/NIWA technical publication: Enting and Lassey (1993). (These calculations use several alternative forms of the pre-1990 land-use flux, none exactly the same as that given in Appendix A). Enting (1991) documents an earlier version of the model and in particular describes calculations contributed to the IPCC (1990) report.

Modellers’ acknowledgements: Keith Lassey’s involvement was funded in part by the State Electricity Commission of Victoria. Cathy Trudinger assisted with the model runs.

Model F, F₂

Name: SLAVE

Description: Scheme for Large-scale Atmosphere- Vegetation Exchange

Modeller: P. Friedlingstein

Institution: Belgian Institute for Space Aeronomy, 3 Ave Circulaire,
B-1180 Brussels, Belgium

Contact: pierre@atmos.oma.be

Summary:

Ocean: None in version F; response function representation in version F₂.

Terrestrial: Nine vegetation types on 5 degree by 5 degree grid. The model has five submodels: vegetation, soil water, carbon, nutrient and CO₂-fertilisation. *Vegetation:* This is based on the data set of Olson (1985). *Soil water:* This uses a 'bucket' model, balancing water supply, actual evapo-transpiration and runoff.

Carbon production: is based on the 'Miami model' of Lieth (1975). For each ecosystem type, the carbon pools are divided into a 2 × 3 grouping as woody vs herbacious and phytomass, litter and soil. The exchanges between components use first-order exchange rates with rate constants depending on climate in some cases.

Nutrient: Nitrogen cycling is modelled. Phosphorus is derived from soil type.

Fertilisation: Net primary production has logarithmic dependence on CO₂ for version F, and hyperbolic dependence on CO₂ for version F₂. The 'beta-factor' depends on both water and nutrients, increasing with water-stress but decreasing with nutrient limitation.

Other processes: Vegetation responds to climatic variation expressed by precipitation and temperature.

Initialisation: Biospheric carbon fluxes and pools are equilibrated with pre-industrial atmosphere.

Calibration: 'Beta-factor' describing fertilisation was tuned to match specified budget over the historical period.

Documentation: Earlier versions of the model have been described by Friedlingstein et al. (1992, 1994).

Versions run: The original version (Model F) was a biota-only model. This was subsequently coupled to a response function representation of the ocean to give Model F₂.

Model G

Name: GLOCO

Description: HILDA ocean and 6 regions by 6 component biota.

Modellers: R.A. Goldstein and A.A. Keller

Institution: Electric Power Research Institute, PO Box 10412 Palo Alto, CA, 94303 USA

Contact: rogoldst@msm.epri.com

Summary:

Both CO₂ and methane are modelled. Single atmospheric reservoir.

Ocean: Oceans are Hilda model of Joos et al. (1991). Inorganic and organic carbon are redistributed within and between the oceans by advection, dispersion and settling. GLOCO simulates the physical and biological cycling of marine phosphorus which influences the rate of organic carbon production.

Terrestrial: Terrestrial component has 6 ecosystems: tropical, temperate and boreal forests; grasslands, tundra and desert. Each ecosystem has 3 living components (foliage, structural and fine roots) and 3 dead components (litter, intermediate soil organic matter and humus). Nitrogen cycling is modelled.

Other: Simulated processes within the terrestrial and oceanic systems are temperature dependent. The user can, for each terrestrial and oceanic ecosystem, either parameterise a function that relates temperature to atmospheric CO₂ or specify an independent temperature scenario.

Calibration: The model was calibrated from 1770 to 1990 by matching the ice-core data of Neftel et al. (1992) and the Mauna Loa data. The initial preindustrial CO₂ concentration is assumed to be 278 ppmv. Ocean chemical concentrations (Takahashi et al., 1991) are assumed close to those observed at present except for small changes in DIC. Redfield ratios follow Takahashi et al. (1985).

Documentation: Oceans: Joos et al. (1991). Terrestrial C and N cycling influenced by the work of Liu et al. (1991), Rastetter et al. (1991), Parton et al. (1987) and Gherini et al. (1985).

Modeller's acknowledgements: The model was developed by R.J.M. Hudson and S.A. Gherini.

Model H

Name: Hamburg Comprehensive Carbon Cycle Model

Description: The Hamburg comprehensive carbon cycle model consists of a three-dimensional oceanic component and a two-dimensional component for the terrestrial biosphere (OBM3m).

Modellers: M. Heimann, J. Kaduk, K. Kurz and E. Maier-Reimer

Institution: MPI für Meteorologie, Bundesstrasse 55, D-20146 Hamburg, Germany

Contact: heimann@dkrz.d400.de

Summary:

Ocean: Three-dimensional Hamburg Model of Oceanic Carbon Cycle (HAMOCC-3) (Maier-Reimer, 1993) based on the flowfield of the large-scale geostrophic oceanic general circulation model LSG (Maier-Reimer et al., 1992). Spatial resolution: approx. 3.5° by 3.5° , 15 layers in the vertical dimension. Temporal resolution: 1 month.

Terrestrial: Modified version of the two-dimensional Osnabrück Biosphere Model (OBM3m) (Esser, 1987, Kaduk and Heimann, 1994). The model describes the cycling of carbon through 5 biospheric carbon pools specified with a horizontal resolution of 2.5° by 2.5° and an annual timestep. The carbon fluxes are formulated as depending on climate through specified annual temperature and precipitation fields. The model includes a CO_2 fertilization parameterization with an approximate hyperbolic functional form but also depending on soil quality. OBM3m specifies the effects of land-use changes by means of a regionally varying distribution fraction of agriculturally used land, based on FAO statistics. Changes in this fraction lead to induced carbon fluxes, both during land clearing and during regrowth if the land is abandoned.

Calibration: The global average of the windspeed dependent gas-exchange coefficient employed by HAMOCC-3 is set to $0.06 \text{ molC m}^{-2} \text{ yr}^{-1}$. This results in a global model bomb- ^{14}C uptake of $9.27 \times 10^9 \text{ atoms cm}^{-2}$ as compared to the observed $8.4 \times 10^9 \text{ atoms cm}^{-2}$ during GEOSECS (Broecker et al., 1985). The globally averaged change in surface ^{14}C concentration due to the bomb- ^{14}C perturbation from 1950 to 1973 predicted by the model is 189‰ as compared to the observed 157‰ (Broecker et al., 1985). The resulting penetration depth of HAMOCC-3 is 320 m, thus approximately 8% lower than the observations.

OBM3m has been tuned in two ways in order to fulfill the IPCC model intercomparison guidelines. Firstly, the agriculturally used land fraction as a function of time was modified such that the model reproduced the prescribed net land-use flux. Secondly, the atmospheric CO_2 budget during the period of atmospheric observations 1960-1989 was balanced by modifying the fertilization parameterization in OBM3m. In the IPCC model intercomparison project experiments, the annual temperature and precipitation input data fields were held time invariant at their standard values (Diaz et al., 1989, Jones et al., 1986).

Documentation: HAMOCC-3 is described in Maier-Reimer (1993), and previous versions in Heinze et al. (1991) (HAMOCC-2) and in Bacastow and Maier-Reimer (1990) (HAMOCC-1). OBM3m is described in Esser (1987) and its modifications in Kaduk and Heimann (1994).

Modeller's acknowledgements: The simulations for the IPCC intercomparison project have been performed partially with support of the Commission of the European Communities (contract EPOC-CT90-0017).

Model J

Description: Hilda ocean model with 4-box terrestrial biota

Modellers: F. Joos and U. Siegenthaler

Institution: Physics Institute, University of Bern, Sidlerstrasse, 5, CH-3012 Bern, Switzerland

Contact: joos@phil.unibe.ch

Summary:

Ocean: The HILDA model is described as version $K(z)$ in Siegenthaler and Joos (1992) and Joos (1992). It has two well-mixed surface boxes in low and high latitudes, a well-mixed high-latitude deep water box and a dissipative interior deepwater box. Tracer transport is by 4 processes: an advective flux giving upwelling in the interior box, diffusion in the interior box and exchange fluxes between the high-latitude-deep and the interior and between the high-latitude-surface and high-latitude-deep. Carbon chemistry uses buffer factors based on Peng et al. (1987). The gas exchange coefficients are the same for low and high latitudes.

Terrestrial: The structure and parameters were as described by Siegenthaler and Oeschger (1987). The model biosphere consists of 4 well-mixed compartments:

- Ground vegetation (100 GtC with 35 Gt C y^{-1} uptake, pre-industrial)
- Wood (500 GtC with 25 Gt C y^{-1} uptake, pre-industrial)
- Detritus (120 GtC, pre-industrial)
- Soil (1200 GtC, pre-industrial)

Fluxes from these reservoirs are taken as proportional to biomass. Gross fertilisation is taken as $\beta \ln[C(t)/C(t_0)] \times 60 \text{ Gt C } y^{-1}$, with $\beta = 0.38$ chosen to fit specified atmospheric budget for 1980's.

Net fertilisation fluxes are taken as the difference between the gross fertilisation flux and the decay of additional biomass accumulated by fertilisation.

Initialisation: For 1765 to 1990, net deforestation was set equal to the sum of net fertilisation and the non-fossil emissions. The latter were deduced by deconvolution of the Siple/Mauna Loa record. Gross deforestation fluxes are obtained by taking into account the reduced decay of biomass due to deforestation. The gross deforestation flux was taken as 12% from ground vegetation, 58% from wood and 30% from soil.

Calibration:

The values of the transport parameters were determined by a least-squares regression to the observed distributions of natural- and bomb- ^{14}C . In order to fit both distributions, the eddy diffusivity was chosen to decrease exponentially with depth. The transport has been checked against CFC-11 and CFC-12 (Joos et al., 1991; Joos, 1992) and ^{39}Ar (Joos, 1992).

Documentation: Siegenthaler and Joos (1992), Joos (1992).

Model L

Name: LLNL Carbon Cycle Model

Description: Upwelling-diffusion model with 6-box terrestrial biota.

Modellers: A. K. Jain and D. J. Wuebbles

Institution: Global Climate Research Division, LLNL, Livermore, CA 94551 USA

Contact: jain1@llnl.gov

Summary:

Ocean: The model ocean consists of a surface layer and a deep ocean which is treated as an advective-diffusive medium with a continuous one-dimensional distribution of dissolved inorganic carbon with transport modelled by eddy diffusivity, K , and upwelling velocity, w . Water upwells through the deep ocean column to the mixed layer from where it is returned, presumably through the polar sea, to the bottom of the ocean column, completing the thermohaline circulation. An additional carbon source term is added to the deep ocean to account for the oxidation of particulate organic carbon. In our model, bottom water concentration is controlled by parameter, π_c , defined as the change in the concentration of the bottom water relative to that in the non-polar region. This parameter is similar to that in the IPCC energy balance model to represent the variation of polar sea temperature. For $\pi_c = 0.5$, the model estimated ocean uptake for 1980–1989 is 2.1 Gt C y^{-1} in agreement with the IPCC estimates. Therefore, we have used $\pi_c = 0.5$ in our model calculations. The buffer factor is calculated from the equations for borate, silicate, phosphate and carbonate equilibrium chemistry and the temperature-dependent equilibrium constants as given by Peng et al. (1987).

Terrestrial: For estimating the biospheric fluxes, a six-box globally aggregated terrestrial biosphere sub-model is coupled to the atmosphere box. The boxes represent ground vegetation, non-woody tree parts, woody tree parts, detritus, mobile soil (turn-over time 75 years), resistant soil (turnover time 500 years). The mass of carbon in the reservoirs and the rates of exchange between them are based on Harvey (1989). The photosynthesis rate is stimulated by increasing CO_2 concentrations via a logarithmic law with fertilization factor $\beta = 0.4$. The rate coefficients are temperature dependent according to an Arrhenius law. A one-dimensional upwelling-diffusion model is used to infer the temperature change. // *Initialisation:* The model is initialised in an inverse mode with prescribed fossil emissions and observed CO_2 concentrations. The fertilization feedback factor is tuned to give land use emissions of 1.6 Gt C y^{-1} averaged over the 1980s. // *Other:* The model is able to consistently simulate different phenomena of the global carbon cycle, in particular the steady state ^{14}C and inorganic carbon distribution in the deep ocean, the anthropogenic CO_2 increase, the corresponding CO_2 dilution effect (Suess effect), and atmospheric ^{13}C as well as the bomb-produced ^{14}C distribution in the ocean.

Calibration: Model dynamic parameters — the eddy diffusivity, K , and upwelling velocity, w , are calibrated by matching the ^{14}C distribution in the deep ocean.

Documentation: The model results of the IPCC modeling exercise are documented in an L.L.N.L internal report (Wuebbles and Jain, 1993). Jain et al. (1994a) describes, in particular, the stabilization calculations contributed to the IPCC (1994) report. The model equations are documented in Jain et al. (1994b) and Kheshgi et al. (1994).

Modellers' Acknowledgments: Work was performed under the auspices of the U. S. D.O.E. at the L.L.N.L. under contract No. W-7405-Eng-48 and was supported in part by the D.O.E. Environmental Science Division. We thank M. Hoffert and H. Kheshgi for helpful comments.

Model M

Description: Twelve-box ocean (calibrated by multiple tracers) and five-box biota.

Modellers: B.H. Braswell, Jr. and B. Moore III.

Institutions: Institute for the Study of Earth, Oceans and Space University of New Hampshire, Durham, NH 03824, USA

Contact: braswell@sage.cgd.ucar.edu

Summary:

Ocean: The ocean model is the 12-box model of Bolin et al. (1983) including detailed handling of the carbonate-borate system.

Terrestrial: Five reservoir model of Emanuel et al. (1984). This has been modified by the inclusion of a fertilisation flux, so that the atmosphere to biota flux is represented as

$$F_{\text{NPP}} = F_{\text{NPP}}(t_0)(1 + \phi) \quad (C.M.1)$$

with

$$\phi = a_1 \tanh(C(t)/C(t_0) + a_2) + a_3 \quad (C.M.2)$$

with the coefficients a_j chosen to fit the missing flux.

Calibration: See Bolin et al. (1983) for ocean calibration technique. Fertilisation flux fitted as described above with $r^2 = 0.8$.

Documentation: Bolin et al. (1983), Emanuel et al. (1984) and Moore and Braswell (1994).

Model O

Name: LODyC OGCM

Description: Ocean GCM, no terrestrial component.

Modellers: J.C. Orr[†] and P. Monfray[‡]

Institutions: [†]Laboratoire de Modélisation du Climat et de l'Environnement, of the CEA (Commissariat à l'Énergie Atomique) Saclay, FRANCE [‡]Centre de Faibles Radioactivités, Laboratoire CNRS F-91198 Gif-sur-Yvette Cedex, FRANCE

Contact: orr@asterix.saclay.cea.fr

Summary:

Ocean: The most recent GCM to estimate the ocean's uptake of anthropogenic CO₂ employs the OPA (Océan Parallélisé) model (Chartier, 1985; Andrich, 1988; Madec and Crépon, 1991; Madec et al., 1991a,b; Blanke and Delecluse, 1993) developed at the Laboratoire d'Océanographie Dynamique et de Climatologie (LODYC, Paris) and converted to a global version by Marti (1992). Anthropogenic CO₂ simulations were recently made at the Laboratoire de Modélisation du Climat et de l'Environnement or LMCE (Orr and Monfray, in prep.). Marti's global model has 19 vertical levels and a grid size that varies between 1° and 2°; hence, its resolution is substantially greater than GCMs used for estimating CO₂ uptake at either Princeton (Sarmiento et al., 1992) or Hamburg (Maier-Reimer and Hasselmann, 1987; Maier-Reimer, 1993).

To allow such high resolution, Marti's model is run in the so-called robust-diagnostic mode, i.e., where potential temperature (θ) and salinity (S) are restored to observations (Levitus, 1982) throughout the water column. In this manner, the model approaches equilibrium relatively rapidly. The circulation field with Marti's model appears quite reasonable. Marti (1992) argues it is (1) better than that of Toggweiler et al.'s prognostic model in several respects, and (2) rather similar to that from Semptner and Chervin (1988), a model with much higher resolution ($\frac{1}{2}^\circ \times \frac{1}{2}^\circ$), but also run in robust-diagnostic fashion.

Marti's robust-diagnostic method differs from that of Toggweiler et al. (1989a) in that restoration of θ and S is relaxed when closer to the equator (similar to Fujio and Imasato, 1991), nearer the coasts (as consideration for more vigorous dynamics particularly near western boundaries), as well as in regions of deep convection.

Tracer studies are run in Marti's off-line version of his model, which runs eight times faster than the on-line version. The off-line version has been validated with simulations for CFC-11 and CFC-12 (Marti, 1992). The LODyC GCM absorbs 2.12 Gt C y⁻¹ during 1980–1989 (Orr, 1993) in its perturbation simulation, analogous to that reported by Sarmiento et al. (1992).

Terrestrial: None

Calibration: This global model has also been validated with both ³H and bomb ¹⁴C, and other validations are under preparation, including simulations for natural ¹⁴C.

Model P

Description: Box-diffusion model

Modeller: T.-H. Peng

Institution: Environmental Sciences Division of Oak Ridge National Laboratory, Oak Ridge, Tennessee, U.S.A.

Contact: pen@pen.esd.ornl.gov

Summary:

Ocean: Box-diffusion model, with surface mixed layer thickness of 75m.

Terrestrial: None

Initialisation: A steady state ocean with pre-industrial atmospheric P_{CO_2} of 280 μatm .

Calibration: Bomb-produced ^{14}C inventory as of mid-point of GEOSECS survey (1975). Also surface water bomb ^{14}C activity at the same time.

Documentation: The ocean model is used to study the contribution of stratospheric inputs to the global inventory of bomb produced radiocarbon. This specific model is documented in Broecker and Peng (1994).

Cases run: S450 and S650

Model Q

Description: Ocean GCM and a model of the terrestrial biosphere, run separately.

Modellers: C. Le Quéré†, J.L Sarmiento† and S.W. Pacala‡

Institution: † Program in Atmospheric and Oceanic Sciences,

‡ Department of Ecology and Evolutionary Biology,

(both of) Princeton University, Princeton, NJ 08544, USA

Contact: lequere@splash.princeton.edu

Summary:

Terrestrial: Six boxes representing the atmosphere, living metabolic tissue, living structural tissue, metabolic litter, structural litter, and soil. The only non-linear term is GPP, calculated as an integral through the canopy:

$$\text{GPP} = \int_0^{B^*} P_{max} e^{\lambda T} \left(\frac{CO_2}{K_{CO_2} + CO_2} \right) \left(\frac{e^{-\alpha B}}{K_L + e^{-\alpha B}} \right) dB \quad (\text{C.Q.1})$$

where B^* corresponds to the leaf layer where photosynthesis equals respiration.

$$P_{max} e^{\lambda T} \left(\frac{CO_2}{K_{CO_2} + CO_2} \right) \left(\frac{e^{-\alpha B}}{K_L + e^{-\alpha B}} \right) = r_m e^{\nu T} \quad (\text{C.Q.2})$$

The first factor in (C.Q.1) governs CO_2 dependence and the second factor governs shading ($K_L=0.25$). α is the product of the light extinction coefficient and a constant giving the ratio of leaf metabolic carbon to total carbon contained in and supporting leaves. Finally, P_{max} governs the maximum rate of photosynthesis, r_m governs the rate of maintenance respiration, and $e^{\lambda T}$ and $e^{\nu T}$ describe, respectively, the dependence of photosynthesis and maintenance respiration on temperature, T . The $e^{\nu T}$ term also governs the temperature sensitivity of decomposition rates.

Ocean: The model is a prognostic world ocean model based on the MOM code from GFDL (Toggweiler et al.,1989: their model P). The resolution is 4.5° of latitude, 3.75° of longitude, and 12 vertical levels of variable thickness with maximum depth of 5000 m. The Indonesian strait (changed since publication) and the Mediterranean sea are closed to advection (one grid box is open only). The annual mean wind stress of Hellerman and Rosenstein is used as an upper boundary condition. Temperature and salinity are restored towards Levitus annual mean values. The carbon uptake is computed using a perturbation approach to a pre-industrial state. Wanninkopf's formulation is used with Esbensen and Kushnir's annual mean wind speed for gas exchange calculations.

Calibration: The global inventory of bomb ^{14}C agrees with the observed inventory within 15%. P_{max} , K_{CO_2} , α , r_m , λ , and ν were estimated by a least squares fit to time series for terrestrial uptake for years corresponding to actual measurements of atmospheric CO_2 .

Documentation: Toggweiler et al. (1989), Sarmiento et al. (1992), Sarmiento and Pacala (1994), Sarmiento et al. (1994).

Modellers' acknowledgements: We would like to thank B. Samuels and J.R. Toggweiler for providing revised ^{14}C results.

n.b. Results for model Q in Release 1 of this report had no terrestrial component.

Model R,R*

Name: IMAGE 2.0

Description: Carbon cycle components of integrated assessment model

Modellers: J. Alcamo, M.S. Krol

Institution: National Institute of Public Health and Environmental Protection P.O. Box 1, 3720 BA Bilthoven, THE NETHERLANDS

Contact: mobijoe@rivm.nl

Summary:

Ocean: The ocean carbon cycle model describes the exchange of carbon between ocean and atmosphere, physical transport, primary production, calcification, decomposition and dissolution. The model includes the elements C (as organic, particulate and dissolved organic), N, O, Ca and ^{14}C , and models the fluxes between the various compartments. The model is defined on a 2-D grid (latitude vs. depth) and distinguishes between Atlantic and Indo-Pacific.

Terrestrial: The Terrestrial Environmental System of IMAGE 2.0 models land cover changes driven by demand for cropland and pasture. Resulting deforestation yields carbon fluxes close to the prescribed scenario. Only in some tropical regions is deforestation assumed to yield direct high carbon releases. Other land cover changes (afforestation) also have a significant effect on the carbon cycle. Terrestrial carbon cycle calculations are performed at grid level using the simulated land cover. NPP is modelled to depend on local climate, vegetation, soil water holding capacity, altitude and atmospheric CO_2 concentration. The model describes 7 carbon pools (in both living and dead biomass), fluxes between these pools and respiration into the atmosphere.

Initialization: The carbon cycle components of IMAGE 2.0 are initialized in equilibrium in 1900 and forced with transient climate and atmospheric CO_2 concentrations but constant land cover up to 1970, the initial year of the integrated model. Model results for the oceanic carbon uptake show a slight dip shortly after 1990, caused by a slight overestimation of 1990 CO_2 concentration by the model and the transition to the prescribed concentration scenario.

Documentation: *Water Air and Soil Pollution* **76**(1,2), 1994: special issue on IMAGE 2.0. in particular: Alcamo et al. (1994), Klein Goldwijk et al. (1994), de Haan et al. (1994)

Versions run: The model was run both with and without feedbacks from climate after 1990. The case with feedbacks is denoted R*, without feedbacks R. Version R is used for the stabilization scenarios (Sx50 and DSx50), version R* is used for the IS92 scenarios. We prefer to use the model R* and to give best estimates of impacts (i.e. including the major feedback processes), considering the obvious use of model results in evaluating emissions scenarios.

Model T

Description: Six reservoir terrestrial component and response function/convolution representation of ocean uptake.

Modeller: L.D.D. Harvey

Institution: Dept. of Geography, University of Toronto, Toronto, Ontario, Canada M5S 1A1.

Contact: harvey@harvey.geog.utoronto.ca

Summary:

Ocean: Response function representation, modified to allow for effects of temperature on solubility of CO₂.

Terrestrial: Six box representation. Fertilisation has logarithmic dependence on CO₂ concentration. Some of the rates are temperature dependent in the standard form of the model.

Other: CO₂-temperature feedbacks did not apply in the runs presented here (Earlier information indicated that feedbacks did apply).

Documentation: Harvey (1989a,b). See also Wigley (1991).

Model V

Description: Empirical response function for deep ocean mixing.

Modeller: J.A. Viecelli

Institution: Lawrence Livermore National Laboratory

Contact: viecelli@newport.llnl.gov

Summary:

Ocean: The model treats the atmosphere and the ocean mixed layer as being in effective equilibrium. The excess carbon from this system dissipates into the deep ocean with a characteristic time constant, τ . Thus an anthropogenic flux, $Q(t)$, gives a rate of change

$$\frac{d}{dt}C(t) = \frac{0.471}{1 + m_f}Q(t) - (C(t) - C_0)/\tau \quad (C.V.1)$$

where m_f describes the partitioning of carbon between the atmosphere and mixed layer.

Terrestrial: None.

Calibration: The time constant for mixing into the deep ocean is taken as $\tau = 240$ yr. on the basis of radiocarbon data. The 1990 values of C and its derivative, as specified in Appendix A, are used to determine $C_0 = 275.42$ ppmv and $m_f = 0.818$.

Model W

Description: The model couples a four-box terrestrial biosphere model with a convolution ocean carbon cycle model.

Modeller: T. Wigley

Institution: Office for Interdisciplinary Earth Studies, UCAR, PO Box 3000, Boulder Colorado, 80307-3000, USA

Contact: wigley@ncar.ucar.edu

Summary:

Ocean: The ocean model is described in Wigley (1991). It uses a convolution representation for ocean uptake following Maier-Reimer and Hasselmann (1987) and Harvey (1989b), in which the Green's function is expressed as a sum of four exponential terms with different weights and decay constants. To partially account for nonlinear effects, three sets of convolution parameters are used with a smooth transition between each determined by the accumulated total emissions level.

Terrestrial: The terrestrial model is similar to one of the hierarchy of box models described by Harvey (1989a). It has a single soil box, a litter/detritus box, and slow and rapid turnover living vegetation boxes. The model includes a CO₂ fertilization effect, which may be chosen to follow a logarithmic form or a rectangular hyperbolic form. Details are given in Wigley (1993).

Forcing: The inputs required are fossil fuel and gross deforestation. Gross deforestation is determined from net deforestation data by calculating regrowth (their difference) as described in Wigley (1993). The computer code for the model includes a number of options for initializing the model to 1990 using either an inverse calculation adjusting the deforestation history to match a prescribed CO₂ concentration history, or a forward calculation with specified net deforestation, and obtaining a best fit to the CO₂ history.

Documentation: Wigley (1991, 1993).

Modeller's acknowledgements: The development of this model was funded under the US Department of Energy grant DE-FG02-86ER60397.

Model Z

Name: Nonequilibrium Model with Integral Coefficients (NMIC).

Description: A 2-box ocean coupled to a single atmospheric reservoir.

Modellers: O.C. Zakharova and K.I. Selyakov

Institution: Climate Change Department, State Hydrological Institute, 199053, 23, St.-Petersburg, Russia

Contact: menzulin@sovam.com

Summary:

Atmosphere-Ocean: Atmospheric reservoir with carbon content, M_a , and two ocean layers of depth $h_1 = 72$ m and $h_2 = 4000$ m, with carbon contents, M_1 and M_2 respectively, which are represented by dimensionless deviations $\Delta_j = (M_j - M_j(t_0))/M_a(t_0)$

Terrestrial: None.

Initialisation: From $P_a = M_a/2.123 = 278$ ppmv in 1765.

Documentation: The model description can be found in: Anthropogenic Climatic Change. 1991. M.I.Budyko and Yu.A.Izrael, Editors. The University of Arizona Press, Tucson. 488 pages.

Additional information: The model is defined by the equations:

$$\frac{d}{dt}\Delta_1 = 12(A_s V_L k_0)(P_a - P_m)/M_a(t_0) - V_{MD} \times (\Delta_1/h_1 - \Delta_2/h_2) \quad (C.Z.1)$$

$$\frac{d}{dt}\Delta_2 = V_{MD} \times (\Delta_1/h_1 - \Delta_2/h_2) \quad (C.Z.2)$$

$$M_a(t) = M_a(t_0) + \int_{t_0}^t Q_{\text{foss}}(t') dt' + \int_{t_0}^t D_n(t') dt' (\Delta_1 + \Delta_2) \times M_a(t_0) \quad \text{for mass balance} \quad (C.Z.3)$$

with $V_{MD} = 6.985 \times 10^{-5}$ cm/s, $V_L = 0.004$ cm/s, Henry's law coefficient $k_0 = 3.32 \times 10^{-2}$ kgMOL/m³/atm, ocean area, $A_s = 3.63 \times 10^{14}$ m², and mixed layer P_{CO_2} , P_m , determined as a function of $\sigma_1 = M_1/h_1/A_s$ using hydrochemical equations for $T = 19.7$ C.

Modeller's acknowledgements: The model was collective work by Prof. Buetner E.K., Dr. Zakharova O.C., Dr. Turchinovich I.Ye., Dr. Lapenis A.G. and Prof. Kobak K.I.

Editorial note: This model was developed for the study of glacial-interglacial changes. The two-box representation is not expected to give accurate descriptions of the changes on time-scales of decades to centuries that are the focus of this report.

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Appendix D: Additional Tables of Results

		A	B	C	E	F	G	H	J	L	M	Q	R	T	W	Z
IS92a	C	Y	Y	-	Y	-	Y	-	Y	Y	-	-	Y	Y	Y	Y
IS92b	C	-	-	-	Y	-	-	-	Y	Y	-	-	Y	-	Y	Y
IS92c	C	-	-	-	Y	-	-	-	Y	Y	-	-	Y	Y	Y	Y
IS92d	C	-	-	-	Y	-	-	-	Y	Y	-	-	Y	-	Y	Y
IS92e	C	-	-	-	Y	-	-	-	Y	Y	-	-	Y	-	Y	Y
IS92f	C	-	-	-	Y	-	-	-	Y	Y	-	-	Y	Y	Y	Y
DEC0%	C	Y	-	-	Y	-	Y	-	Y	Y	-	-	-	-	Y	Y
DEC1%	C	Y	-	-	Y	-	Y	-	Y	Y	-	-	-	-	Y	Y
DEC2%	C	Y	-	-	Y	-	Y	-	Y	Y	-	-	-	-	Y	-
Iinit	G_a	-	-	-	Y	-	Y	Y	Y	Y	-	-	-	-	Y	-
Ipert	G_a	-	-	-	Y	-	Y	Y	Y	Y	-	-	Y	-	Y	-
Iinit	G_{oc}	-	-	-	-	S	-	Y	Y	Y	-	Y	-	S	S	-
Ipert	G_{oc}	-	-	-	-	S	-	Y	Y	Y	-	Y	-	S	S	-
Iinit	G_{bio}	-	-	-	-	-	-	Y	-	-	-	-	-	-	-	-
Ipert	G_{bio}	-	-	-	-	-	-	Y	-	-	-	-	-	-	-	-
S650	E	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
S450	E	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
S350	E	Y	Y	-	Y	Y	Y	-	Y	Y	-	Y	Y	Y	Y	Y
S550	E	Y	Y	-	Y	Y	-	-	Y	Y	-	Y	Y	Y	Y	Y
S750	E	Y	Y	-	Y	Y	-	-	Y	Y	-	Y	Y	Y	Y	Y
DS550	E	Y	Y	-	Y	Y	-	-	Y	Y	-	Y	Y	Y	Y	Y
DS450	E	Y	Y	-	Y	Y	-	-	Y	Y	-	Y	Y	Y	Y	Y
S650	S_{ocean}	Y	Y	-	-	Y	-	Y	Y	Y	Y	Y	Y	Y	Y	-
S450	S_{ocean}	Y	Y	-	-	Y	-	Y	Y	Y	Y	Y	Y	Y	Y	-
S350	S_{ocean}	Y	Y	-	-	Y	-	-	Y	Y	-	Y	Y	Y	Y	-
S550	S_{ocean}	Y	Y	-	-	Y	-	-	Y	Y	-	Y	Y	Y	Y	-
S750	S_{ocean}	Y	Y	-	-	Y	-	-	Y	Y	-	Y	Y	Y	Y	-
DS550	S_{ocean}	Y	Y	-	-	Y	-	-	Y	Y	-	Y	Y	Y	Y	-
DS450	S_{ocean}	Y	Y	-	-	Y	-	-	Y	Y	-	Y	Y	Y	Y	-
S650	S_{fert}	Y	-	-	-	Y	-	Y	Y	Y	-	Y	Y	Y	Y	Y
S450	S_{fert}	Y	-	-	-	Y	-	Y	Y	Y	-	Y	Y	Y	Y	Y
S350	S_{fert}	Y	-	-	-	Y	-	-	Y	Y	-	Y	Y	Y	Y	Y
S550	S_{fert}	Y	-	-	-	Y	-	-	Y	Y	-	Y	Y	Y	Y	Y
S750	S_{fert}	Y	-	-	-	Y	-	-	Y	Y	-	Y	Y	Y	Y	Y
DS550	S_{fert}	Y	-	-	-	Y	-	-	Y	Y	-	Y	Y	Y	Y	Y
DS450	S_{fert}	Y	-	-	-	Y	-	-	Y	Y	-	Y	Y	Y	Y	Y

Table D.1. Calculations contributed. In addition, Models O, P and V (all ocean-only models) each contributed E and S_{ocean} for S650 and S450. ‘Y’ denotes calculations contributed, ‘S’ denotes ocean impulse response function specified directly to define model. The biotic fluxes S_{fert} are supplied either as net biotic flux or as the fertilisation component only, to be combined with net flux from land-use change.

Model	C(1765)	C(1900)	C(1950)	C(1970)	C(1980)	C(1990)	$\frac{dC}{dt}$ (1990)
A ₂		293.70	309.41	326.49	339.91	353.83	1.59
E ₁	281.07	293.53	308.88	325.57	339.34	354.37	1.69
V _A	275.47	290.13	308.36	325.09	338.64	354.17	1.70
V _B	277.95	291.95	308.62	325.15	338.84	354.17	1.67

Table D.2. Details of forward initialisations.

Model	1850	1900	1950	1960	1970	1980	1990
A ₁	0.28	0.51	0.82	1.01	1.34	1.81	2.25
A ₂	0.08	0.32	0.75	1.07	1.46	1.88	2.18
B	0.35	0.63	1.00	1.24	1.65	2.21	2.74
E	0.20	0.40	0.80	1.10	1.50	2.00	2.30
F ₂	0.26	0.48	0.81	0.99	1.30	1.77	2.27
H	0.18	0.36	0.59	0.74	0.99	1.32	1.63
J	0.30	0.54	0.86	1.08	1.45	1.94	2.41
L	0.28	0.51	0.81	1.04	1.44	1.95	2.38
M	0.28	0.48	0.77	0.93	1.19	1.55	1.90
O	0.31	0.57	0.94	1.13	1.45	1.89	2.36
P	0.31	0.56	0.88	1.10	1.46	1.96	2.43
Q	0.44	0.74	1.15	1.38	1.79	2.39	2.98
R						1.42	1.63
T	0.28	0.49	0.78	0.94	1.20	1.59	1.98
W	0.29	0.54	0.89	1.07	1.37	1.81	2.24
Z	0.71	1.21	1.95	2.26	2.77	3.44	4.20

Table D.3. Ocean fluxes pre-1990.

Model	1850	1900	1950	1960	1970	1980	1990
A ₁	-0.30	-0.50	-0.68	-0.86	-1.17	-1.64	-2.04
A ₂	-0.14	-0.36	-0.70	-0.99	-1.35	-1.78	-1.98
T	-0.30	-0.51	-0.76	-0.91	-1.19	-1.69	-2.21
W	-0.30	-0.55	-0.87	-1.00	-1.22	-1.52	-1.95

Table D.4. Fertilisation fluxes pre-1990.

Model	2000	2050	2100	2150	2200	2300
A	7.25	9.17	8.91	6.16	3.03	2.05
B ₁	6.17	8.23	9.59	7.79	5.18	4.51
B ₂	5.98	8.26	9.95	8.12	5.62	5.01
B ₃	6.88	8.99	9.27	7.02	4.35	3.57
E	7.36	10.10	10.13	7.16	3.68	2.15
F ₂	7.54	11.72	13.39	11.26	7.49	4.82
H	7.11	8.57	8.35	5.79	3.16	2.38
J	7.21	9.89	10.10	7.30	3.88	2.31
L	7.33	9.80	9.75	6.80	3.25	1.99
M	6.73	8.68	9.20	5.32	2.88	2.18
Q	8.33	11.00	10.93	7.98	4.49	2.95
R	5.66	10.55	9.21			
T	7.26	9.77	10.44	7.89	4.51	3.04
W	7.20	10.43	11.19	8.78	5.58	3.74
O	5.25	7.65	8.31	6.33		
P	5.26	7.20	7.44	5.22	2.65	1.96
Z	7.58	12.13	13.66	11.44	7.93	4.89
G	6.10	13.70	6.11	2.34	1.50	
V _A	8.77	16.89	8.37	1.92	0.37	

Table D.5. Industrial emissions for S650.

Model	2000	2050	2100	2150	2200	2300
A	6.72	4.86	2.41	1.63	1.36	1.11
B ₁	5.64	4.20	3.61	3.57	3.54	3.40
B ₂	5.47	4.52	4.22	4.15	4.08	3.97
B ₃	6.37	5.25	3.54	3.05	2.81	2.52
E	6.83	5.72	3.18	2.04	1.53	1.11
F ₂	7.00	6.94	4.78	3.47	2.23	1.89
G	6.10	3.33	1.49	1.49	1.49	
H	6.57	4.89	3.01	2.26	1.89	1.46
J	6.63	4.89	3.01	2.26	1.89	1.46
L	6.78	5.31	2.72	1.76	1.39	1.01
M	6.26	5.35	4.07	1.79	1.55	1.27
Q	7.74	6.53	3.75	2.62	2.14	1.64
R	5.43	6.71	3.14			
T	6.76	5.32	2.95	1.90	1.53	1.15
W	6.66	6.19	4.29	3.31	2.73	2.20
O	4.75	4.11	2.76	2.27	1.95	
P	4.76	3.60	1.97	1.53	1.32	1.07
Z	5.00	6.87	6.33	5.16	4.21	2.80
V _A	6.89	4.13	3.15	2.86	2.82	
V _B	7.26	6.19	5.78	5.57	5.55	

Table D.6. Industrial emissions for S450.

Model	0	10	25	50	100	200	300	400	500
H	1.0	0.782	0.678	0.585	0.474	0.346			
J	1.0	0.697	0.568	0.470	0.376	0.293	0.250	0.223	0.205
L	1.0	0.739	0.629	0.536	0.439	0.345	0.296	0.268	0.253
Q	1.0	0.757	0.619	0.508	0.402	0.310			
W	1.0	0.746	0.602	0.476	0.364	0.267	0.222	0.195	0.177

Table D.7. Equilibrium response function, ocean only.

Model	0	10	25	50	100	200	300	400	500
H	1.0	0.820	0.731	0.645	0.535	0.399			
J	1.0	0.747	0.658	0.594	0.556	0.526	0.490	0.461	0.439
L	1.0	0.840	0.764	0.709	0.668	0.625	0.575	0.539	0.517
Q	1.0	0.796	0.694	0.623	0.575	0.551			
W	1.0	0.801	0.688	0.574	0.493	0.436	0.391	0.333	0.282

Table D.8. Perturbation response function, ocean only.

Model	0	10	25	50	100	200
H	1.0	0.517	0.350	0.275	0.230	0.202

Table D.9. Equilibrium response function, biota only.

Model	0	10	25	50	100	200
H	1.0	0.765	0.610	0.496	0.409	0.352

Table D.10. Perturbation response function, biota only.

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Appendix E: Additional Figures

This appendix contains plots of calculated results that fill out the picture given by the selected examples in the body of the text. This means that sets of related plots will be partly in this appendix and partly in the main text. The natural groupings are:

IPCC 1992 scenarios This set of figures shows the atmospheric CO₂ concentrations from forward calculations using the 6 IPCC 1992 scenarios: Figures 7.1 (IS92a), E.8 (IS92b), E.9 (IS92c), E.10 (IS92d), E.11 (IS92e) and E.12 (IS92f).

Science profiles This set of forward calculations uses specified percentage changes from 1995 emissions. The calculated CO₂ concentrations are shown in Figures 7.2 (DEC0%, i.e. emissions stabilised at 1995 levels), E.6 (DEC1%) and E.7 (DEC2%).

Emissions for stabilisation This set of figures shows the results of the inverse calculations which deduce the industrial (fossil) emissions required to achieve the concentration profiles specified in Figure 8.1. The results are in Figures 8.2 (S450), 8.3 (S650), E.1 (S350), E.2 (S550), E.3 (S750), E.4 (DS450) and E.5 (DS550). As discussed earlier, for the purposes of the Framework Convention on Climate Change, an analysis in terms of total anthropogenic emission might have been preferable. The curves can be converted to the anthropogenic total by adding the prescribed 'land-use' flux shown in Figure B.4.

Integrated emissions for stabilisation This group shows the cumulative industrial emissions from 1990 onwards for the stabilisation cases. These are Figures 8.6a (S650), E.13a (S350), E.14a (S450), E.15a (S550) and E.16a (S750). To convert to the integrals of total anthropogenic emissions, the integral (from 1990) of the land-use flux shown in Figure B.4 must be added. This is relatively small and after 2100 it is a constant 82 GtC.

Integrated oceanic uptake for stabilisation These show the cumulative ocean uptake from 1990 for the stabilisation calculations. The prescribed atmospheric concentration for each case is shown as the dashed curve. These are Figures 8.6b (S650), E.13b (S350), E.14b (S450), E.15b (S550) and E.16b (S750). The vertical scale on each of these plots is half that of the corresponding plots for cumulative industrial emissions.

Impulse responses The various cases of impulse response functions are shown in Figures 9.1 (pre-industrial), 9.2 (relative to S650) and 9.3 (calculated using Model J, including the reference case used to define GWPs).

In the majority of figures in this appendix, dashed curves are used to denote cases calculated with climatic feedbacks included (Models R* and T).

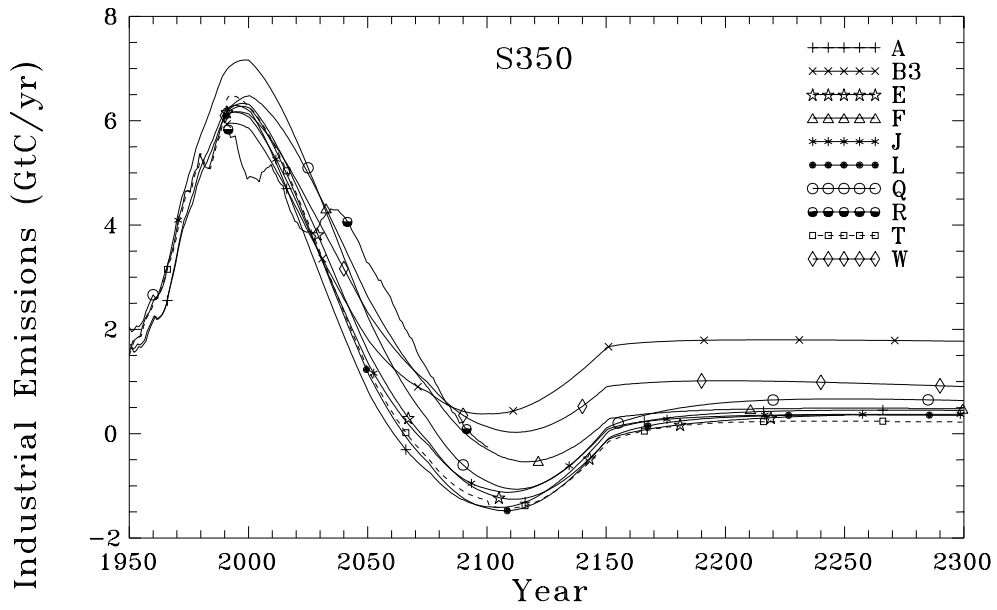


Figure E.1. Calculated industrial emissions for S350 case.

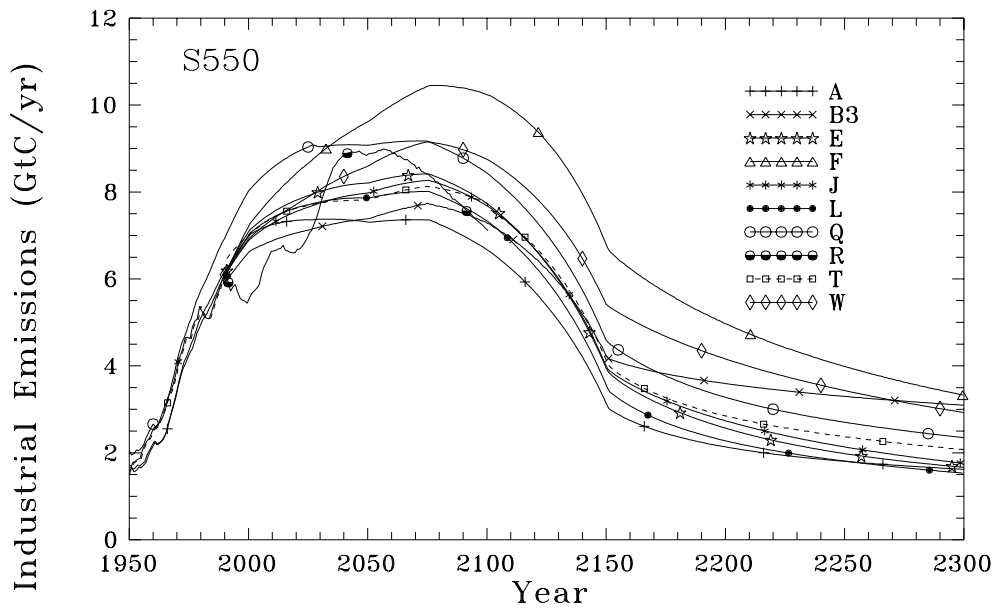


Figure E.2. Calculated industrial emissions for S550 case.

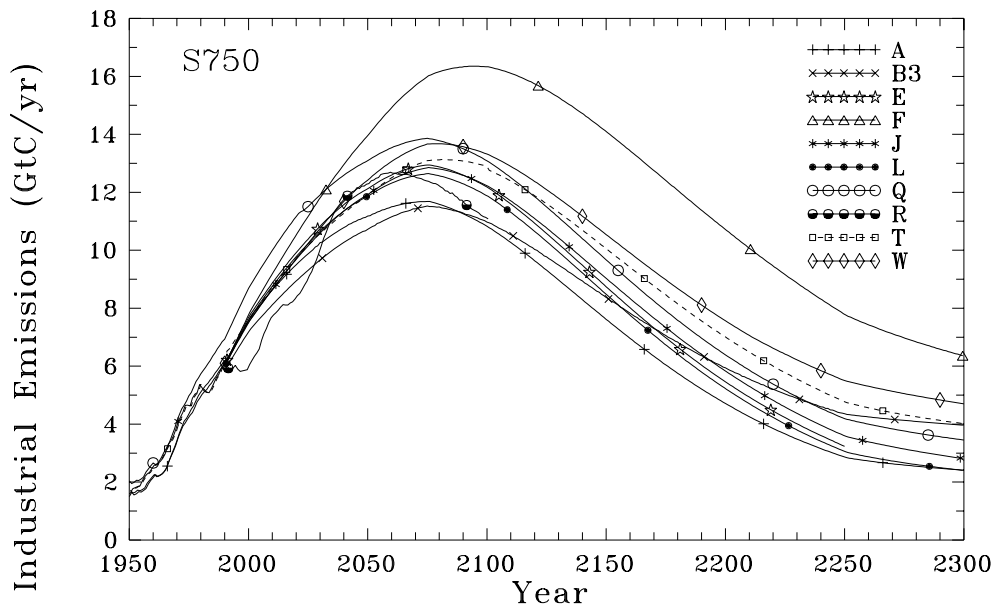


Figure E.3. Calculated industrial emissions for S750 case.

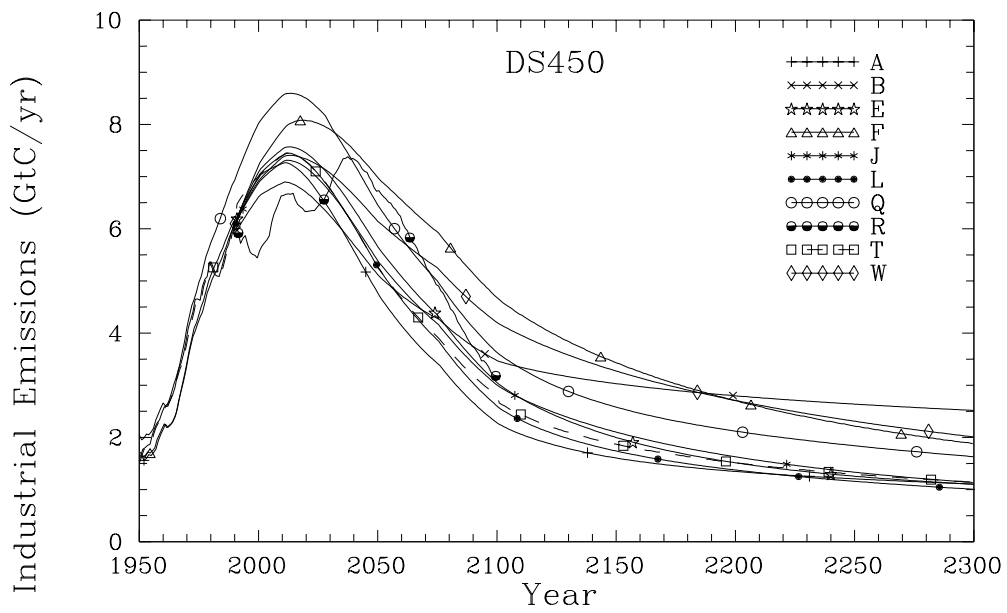


Figure E.4. Calculated industrial emissions for DS450 case.

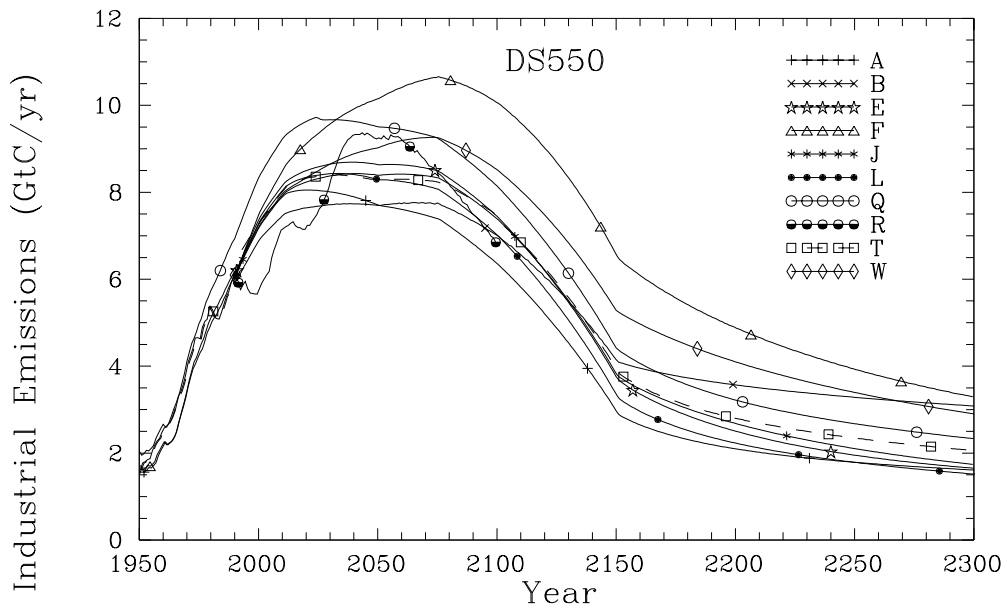


Figure E.5. Calculated industrial emissions for DS550 case.

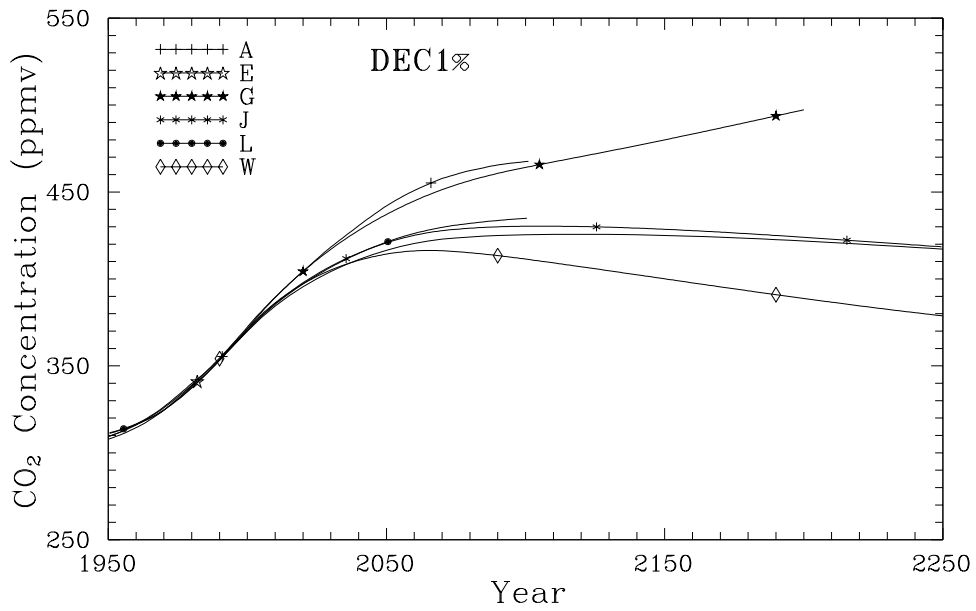


Figure E.6. Concentrations for 1% compound emission reduction.

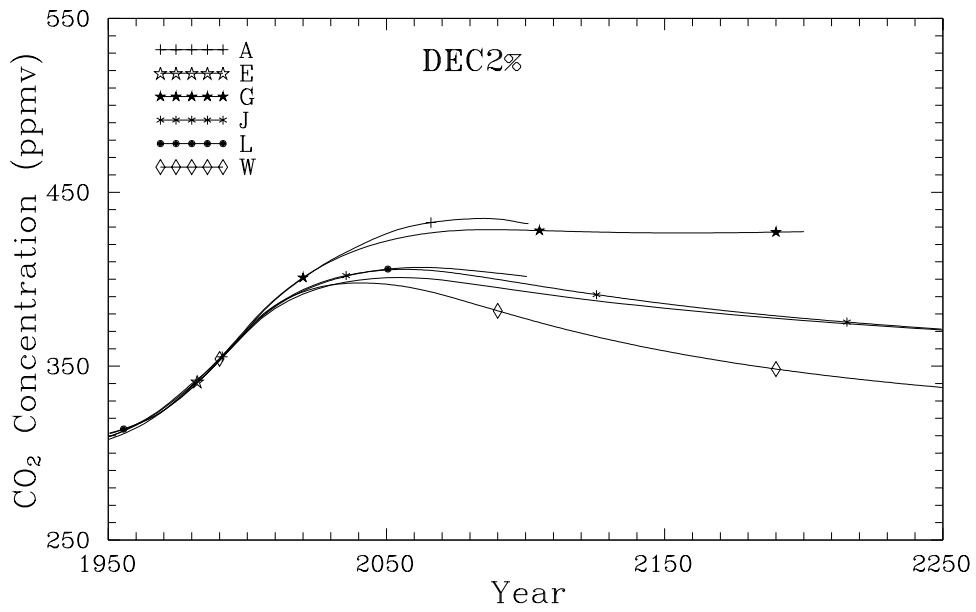


Figure E.7. Concentrations for 2% compound emission reduction.

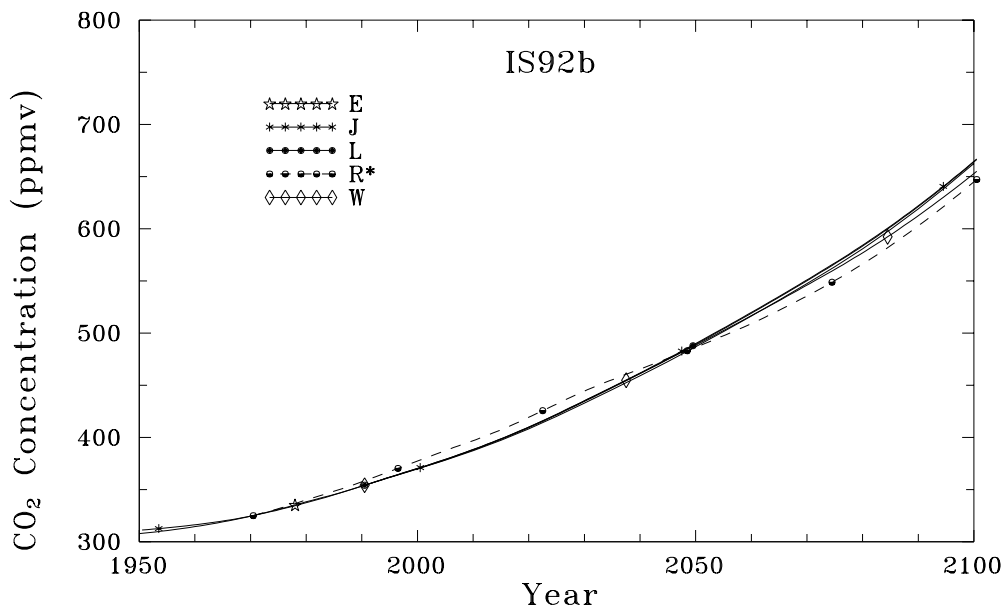


Figure E.8. Concentrations predicted using IS92b.

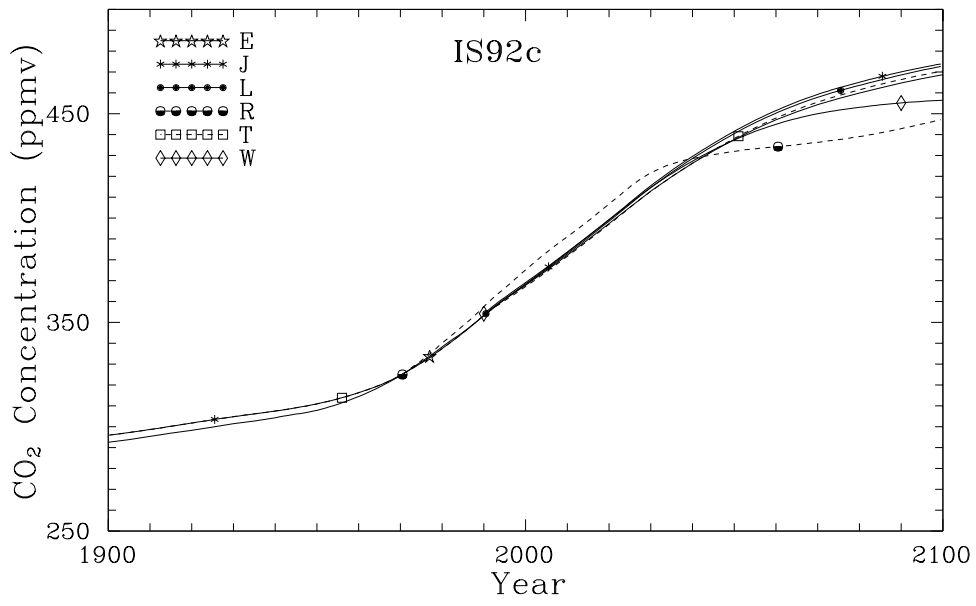


Figure E.9. Concentrations predicted using IS92c.

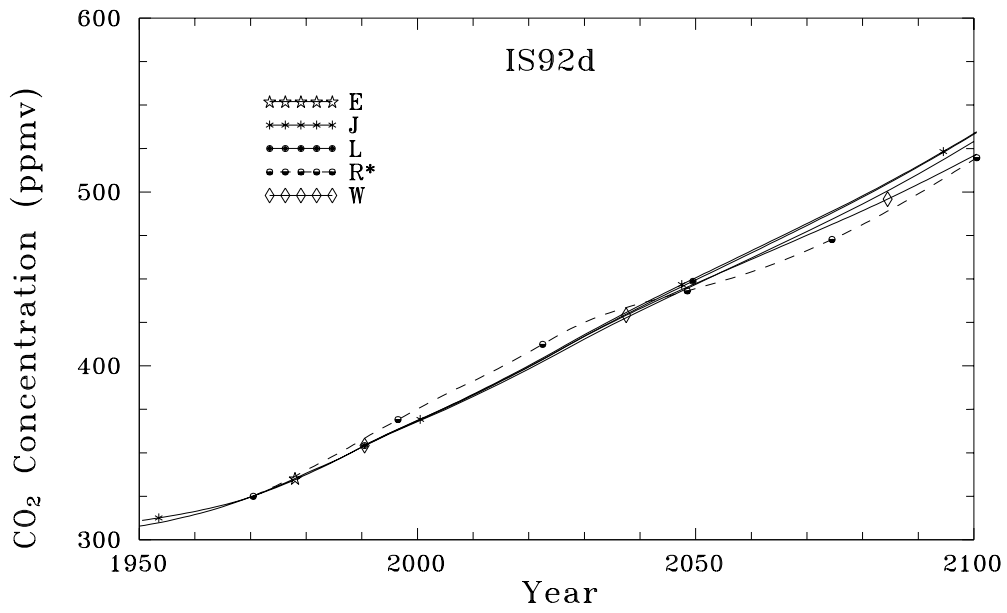


Figure E.10. Concentrations predicted using IS92d.

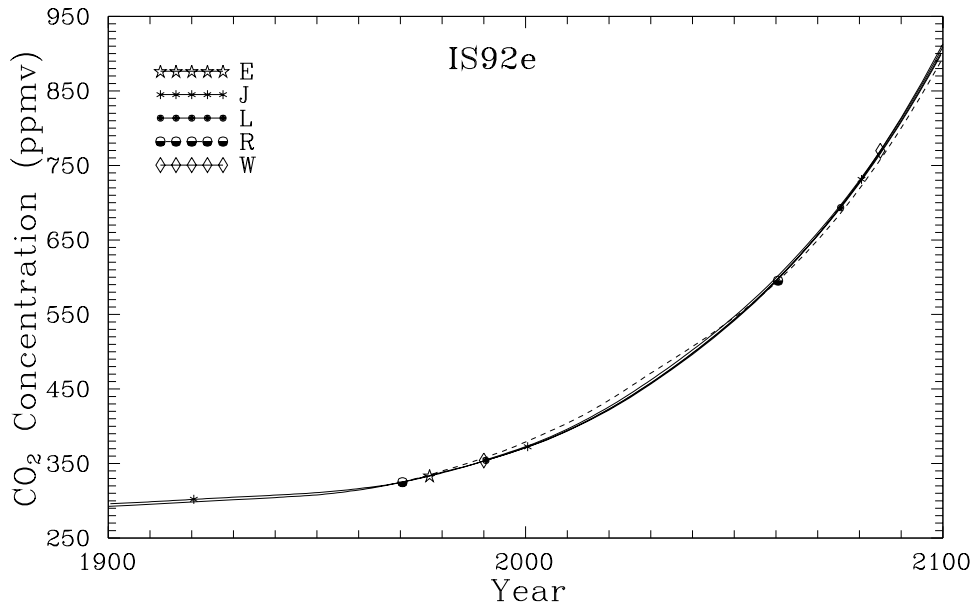


Figure E.11. Concentrations predicted using IS92e.

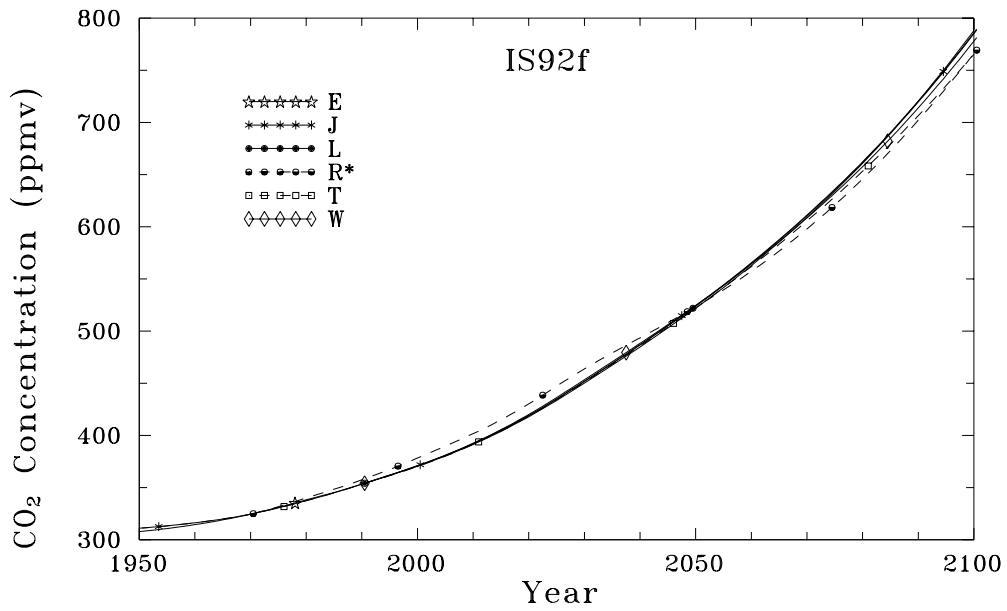


Figure E.12. Concentrations predicted using IS92f.

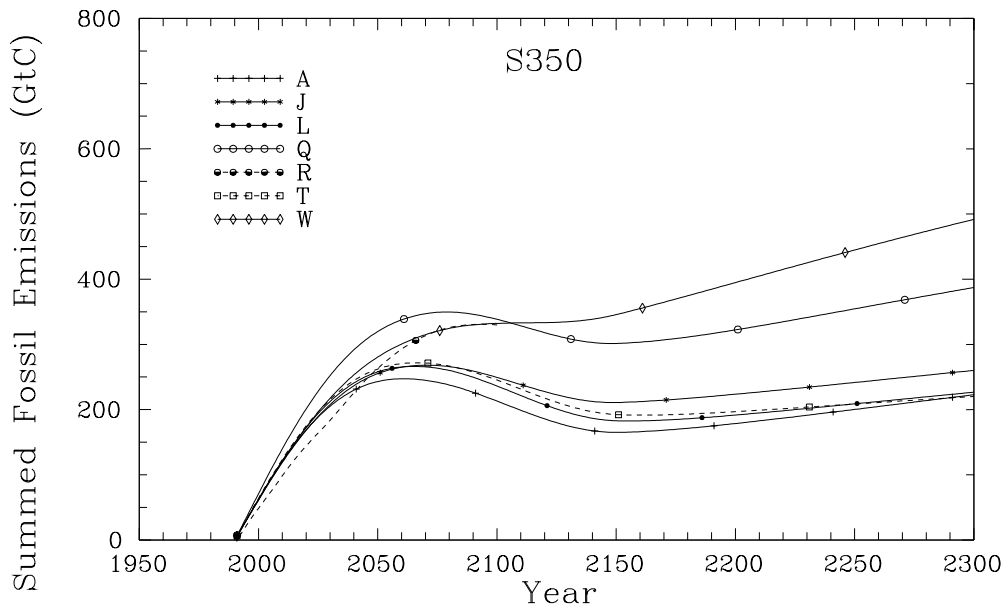


Figure E.13a. Integrated industrial emissions for S350.

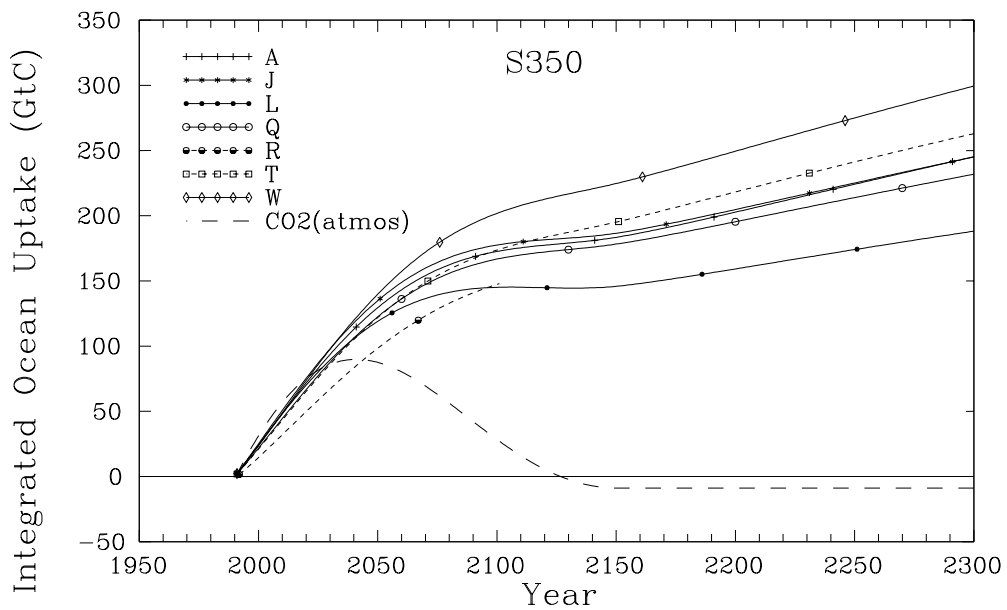


Figure E.13b. Integrated oceanic uptake for S350. Here and in 14b, 15b and 16b, the longer dashes denote the change in atmospheric carbon inventory, relative to 1990.

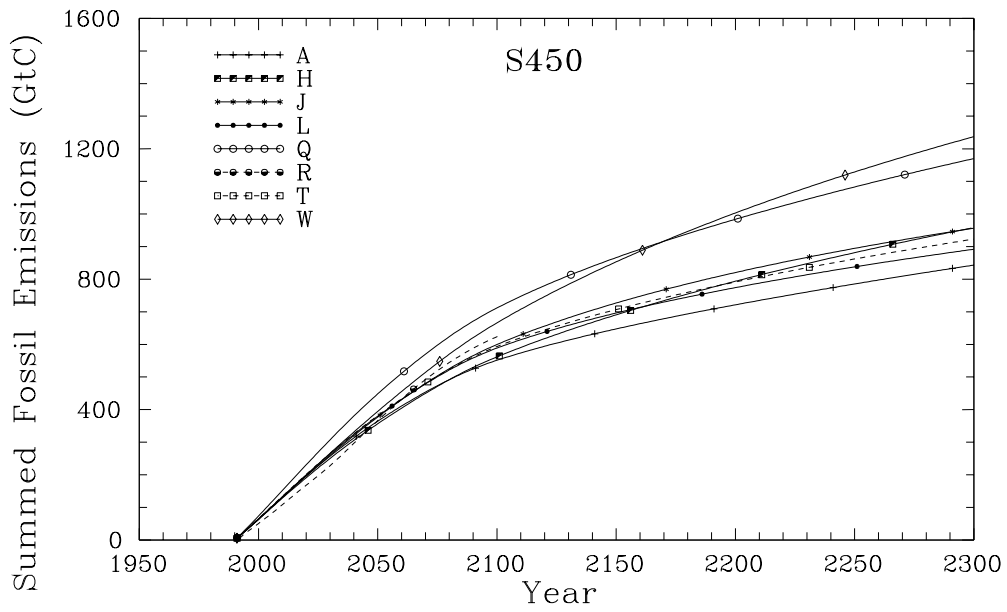


Figure E.14a. Integrated industrial emissions for S450.

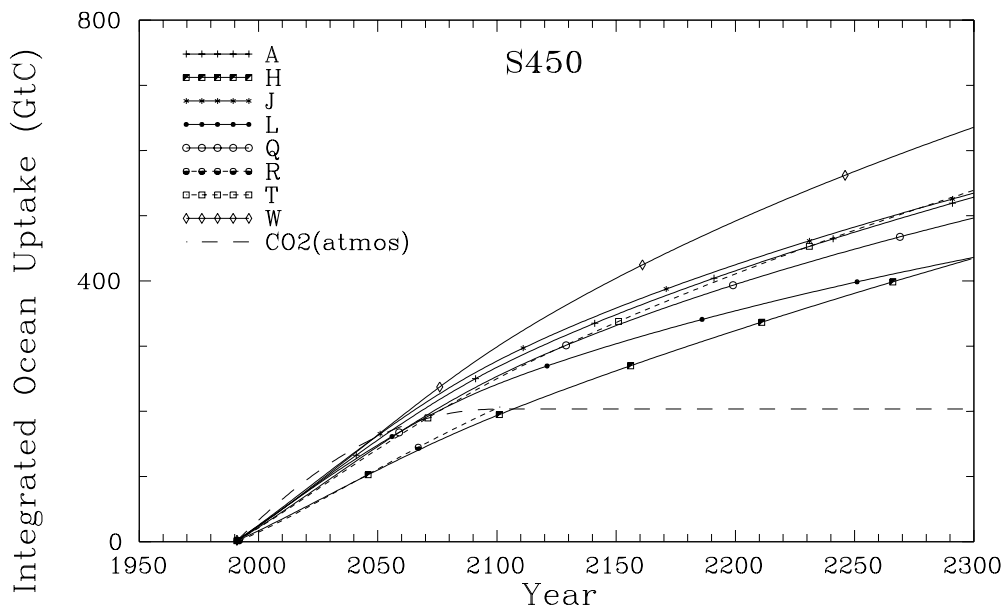


Figure E.14b. Integrated oceanic uptake for S450.

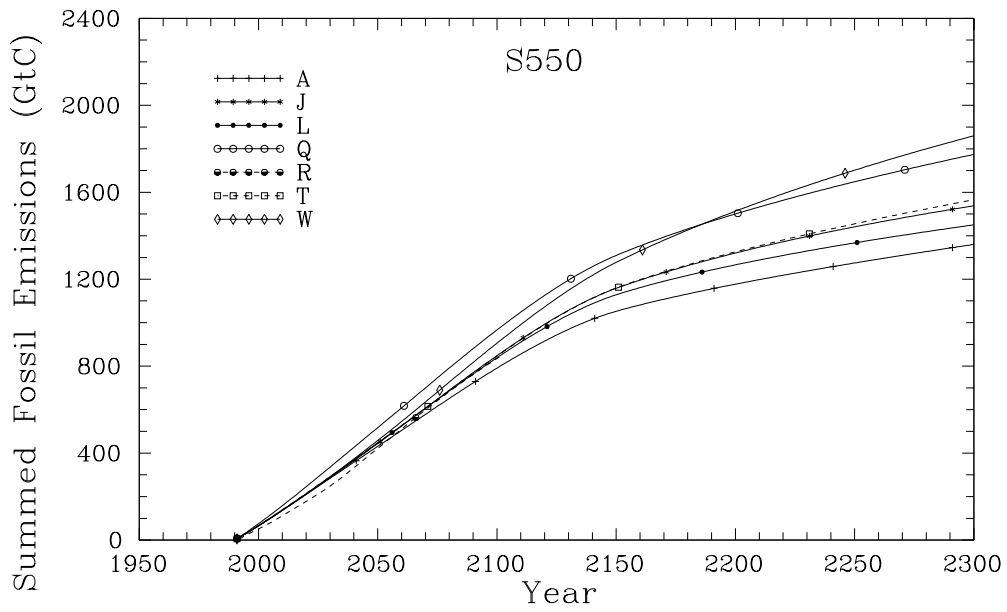


Figure E.15a. Integrated industrial emissions for S550.

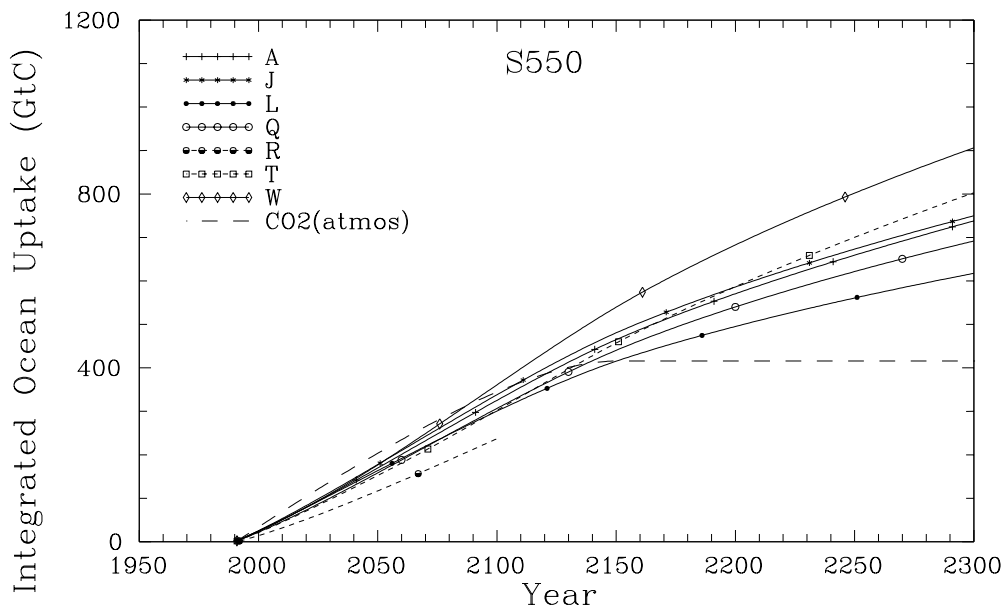


Figure E.15b. Integrated oceanic uptake for S550.

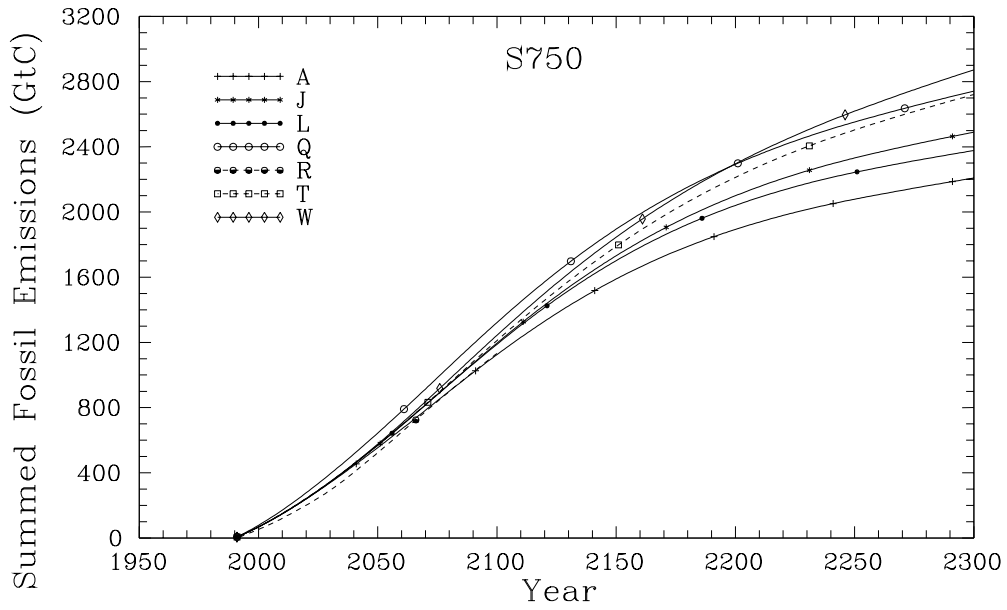


Figure E.16a. Integrated industrial emissions for S750.

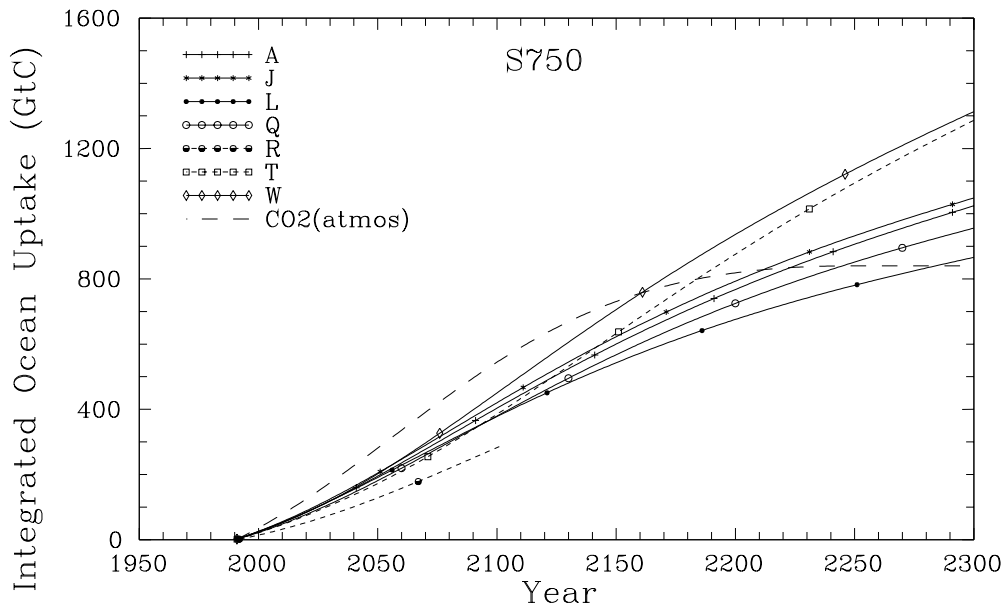


Figure E.16b. Integrated oceanic uptake for S750.

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Appendix F: Additional Calculations

In addition to the standard calculations specified in Appendix A, a number of the modelling groups performed additional calculations that did not follow the specifications.

Some of these are mentioned in the body of the report, particularly those that provide a basis for comparison with our 'core' results. Some are included in the various figures and tables, flagged as 'non-standard' cases. In this appendix we list these and additional 'non-standard' calculations. Some of these results may be obtainable from the Carbon Dioxide Information Analysis Center. In other cases, results may be obtainable from the individual modellers.

The cases discussed in the report are:

Feedback Model R* includes effects of feedbacks from climate change. This is discussed in Section 12b. For Model T, the information regarding the inclusion of temperature feedbacks was inconsistent.

WEC scenarios These additional scenarios are discussed in Section 12a. The only calculations are from Model W.

Alternative terrestrial representation Model B was used for the 7 stabilisation cases and for IS92a. For each of these histories, 3 sets of calculations were run, differing in the way the terrestrial component was treated. One set use the prescribed 'land-use' flux while the others simulated the land-use flux by calculations within the model. In all cases a residual flux was estimated from an inverse initialisation and was extrapolated into the future as a constant. This is discussed in Section 12c.

Other calculations contributed are:

Model B In addition to the calculations described above, Model B was used to estimate the decline in atmospheric CO₂ given zero emissions after 1990, using the total model and the ocean-only component.

Model G In this case, the concentration profiles for stabilisation differed from those specified. For stabilisation at 450 ppmv, the difference is small. For stabilisation at 650 ppmv, the target date for stabilisation was earlier, giving a profile with an effective compression of the time-scale. This led to emission estimates which, compared to models using the specified profile, were initially higher and then had a more rapid decline after the peak. Figure 8a shows the integrated emissions.

The profile that was used was intended to follow a 'business-as-usual' type of emission history for as long as possible consistent with achieving the specified stabilisation.

Model J This model was used to define a reference response function to be used in the definition of Global Warming Potentials (see Section 9). This was defined as the response relative to an emission profile designed to give constant concentrations from 1990 onwards. The response was defined using a 10 GtC pulse injected in 1995. In addition, two other response functions were calculated using Model J. These were defined by adding 10 GtC pulses in 1995 to the DEC0% and IS92a emissions.

Model V The concentration profile for S650 differed from that specified. This was intended to correspond to a depletion of fossil fuel reserves.

Model Z An additional forward calculation used a scenario from Bashmakov.

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Appendix G: Notation

C_0	Initial (mean pre-industrial) atmospheric CO ₂ concentration.
$C(t)$	Atmospheric CO ₂ concentration at time t , in ppmv.
$D_n(t)$	Net carbon flux from land-use change.
$D_g(t)$	Gross carbon flux from land-use change.
F	Radiative forcing.
F_X	Radiative forcing due to constituent X .
G	Generic notation for response functions (Green's functions).
g	Laplace transform of G .
G_a	Total atmospheric response function.
g_a	Laplace transform of G_a .
$G_{a:bio}$	Function defining response of biota to atmospheric perturbation.
$g_{a:bio}$	Laplace transform of $G_{a:bio}$.
$G_{a:oc}$	Function defining response of ocean to atmospheric perturbation.
$g_{a:oc}$	Laplace transform of $G_{a:oc}$.
N_a	Excess atmospheric carbon (in Gt) = $2.123[C(t) - C_0]$.
n_a	Laplace transform of N_a .
N_b	Perturbation to biotic carbon reservoir (excluding land-use term).
n_b	Laplace transform of N_b .
N_o	Perturbation to ocean carbon content.
n_o	Laplace transform of N_o .
p	Laplace transform variable.
$Q, Q(t)$	Total anthropogenic source, = $Q_{foss} + D_n$
$q(p)$	Laplace transform of $Q(t)$.
Q_{foss}	Fossil carbon source.
$Q_{foss}(t)$	Fossil carbon source.
r	Airborne fraction: \dot{N}_a/Q
\bar{r}	Average airborne fraction $\Delta N_a / \int Q dt$
S	Generic notation for sinks.
S_{ocean}	Net ocean carbon sink.
S_{fert}	CO ₂ sink from CO ₂ -fertilisation.
S_{resid}	Residual CO ₂ sink.
t	Time in years.
t_s	Time of stabilisation of concentration.
z_{pen}	Penetration depth for bomb- ¹⁴ C.
$\delta(t)$	Dirac delta function.

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Appendix H: Glossary

- Advection** Transport by large scale motion (of the ocean in the context of this report).
- Airborne fraction** The proportion of CO₂ emissions remaining in the atmosphere.
- Anthropogenic CO₂ flux** Defined as being the net carbon input to the atmosphere due to human influence but excluding natural responses to such input. The precise distinctions are somewhat arbitrary: we include all the fossil (industrial) source, plus the net carbon flux associated with current and past changes in land-use.
- Bomb-¹⁴C** Excess ¹⁴C due to atmospheric testing of nuclear weapons.
- Buffer factor** (Revelle factor) Specification of the relation between CO₂ partial pressure and total inorganic carbon in the ocean surface.
- Eddy diffusion** Mathematical representation of large-scale mixing.
- ENSO** El-Nino/Southern Oscillation. Combined interannual fluctuation in atmosphere/ocean properties. The atmospheric component (Southern Oscillation) is characterised by abnormal east-west pressure gradients across the Pacific. The ocean component (El Nino) is characterised by abnormally warm waters in the eastern Pacific. There is a small-scale variation in atmospheric CO₂ correlated with ENSO events.
- Feedback** Process where a response to some forcing acts to change the amount of forcing: ‘positive feedback’ if the response adds to the forcing and ‘negative feedback’ if the response counteracts the forcing.
- CO₂-Fertilisation** The effect of higher CO₂ levels in producing greater plant growth. The direct effect on growth is well established by laboratory studies on many species. However the key issue for the problems discussed in this report is the extent to which such enhanced growth leads to a sustained increase terrestrial carbon.
- Fossil CO₂ source** The earlier IPCC (1990, 1992) reports denoted this component as ‘industrial’, referring to the production rather than the end-use. This component includes use of fossil fuel (and ideally losses such as leakage and gas flaring) non-fuel uses of fossil carbon (to the extent that such products are oxidised to CO₂) and production of cement.
- Forward** Calculation where the chain of inference follows the direction of cause and effect. In the present context, deducing atmospheric CO₂ concentrations from specified emissions. (c.f. *inverse*).
- GCM** General Circulation Model. Computer model of the atmosphere (AGCM) or ocean (OGCM) that solves (approximately) the dynamical equations which determine the atmospheric (or oceanic) motion.
- GEOSECS** Geochemical Ocean Sections. An observational program conducted during 1973–74. The most important data for carbon cycle studies are the ¹⁴C profiles.
- GtC** Gigatons of carbon. 1 Gt = 10¹⁵ g. Carbon is exchanged between reservoirs, taking a range of chemical forms and so, for uniformity, the amounts are characterised in terms of the mass of carbon. 1 GtC corresponds to $\frac{44}{12}$ Gt of CO₂. One of the few contexts in which the mass of CO₂ is used is in GWPs defined per unit mass.
- GWP** Global Warming Potential. Numerical index designed to facilitate comparisons between radiatively active gases.

Industrial CO₂ See fossil.

Inverse Calculation where the chain of inference reverses the direction of cause and effect. In the present context, using specified atmospheric CO₂ concentrations to deduce the emission histories that would produce these concentrations. (c.f. *forward*).

IPCC Intergovernmental Panel on Climate Change. A body established by the World Meteorological Organisation and the United Nations Environment Program.

KOALA Key Ocean/Atmosphere/Land Assessments. Working title of this document.

Koala Australian marsupial with a six-foot long appendix.

Land-use change flux This is defined as the net carbon flux to the atmosphere from current and past changes in land-use, e.g. deforestation, regrowth, conversions between cropland and pasture, etc. The changes in soil carbon associated with such changes can continue for many decades after the original change in land-use.

Mixed layer Surface layer of the ocean with relatively little variation in the vertical direction due to the action of surface wind stress.

ppmv Parts per million by volume. Measure of trace gas content. The unit ppmv is a measure of atmospheric mixing ratio, although common usage is to apply the term concentration (incorrectly) as equivalent. CO₂ mixing ratios are generally expressed relative to dry air.

Pre-industrial Period prior to the large increase in fossil carbon emissions, i.e. before about 1800 or 1750.

Profile Specification of future variation expressed as a function of time without reference to specific societal actions. (c.f. *scenario*).

Radiative Forcing Influence perturbing the radiative balance of the earth.

Reservoir A part of the earth/ocean/atmosphere system treated as a single entity in terms of its carbon content for purposes of description or modelling.

Response Function Mathematical function of time, specifying the proportion of a unit perturbation remaining after time t .

Scenario Specification of future variation (particularly with reference to CO₂ emissions in this report) derived from specific assumptions about societal behaviour. (c.f. *profile*).

Sink Process leading to net removal of carbon from the atmosphere.

Source Process giving a net input of carbon to the atmosphere.

STUGE An integrated assessment model for greenhouse change studies.

TTO Transient Tracers in the Ocean. An ocean measurement program.

WOCE World Ocean Circulation Experiment. An ongoing (1994) program measuring physical and chemical properties of the oceans.

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Ulrich Siegenthaler 1941–1994

Uli Siegenthaler was born in Frutigen, Switzerland in 1941.

The formal milestones of his scientific career are:

1960-66 Studies in physics at the Eidgenössische Technische Hochschule, Zurich.

1966 Diploma thesis (Master's degree) in physics.

1967-71 Doctorate studies at Physics Institute, University of Bern (Prof. H. Oeschger)

1971 Dr. phil. nat. (Ph.D.) summa cum laude. Thesis subject: Oxygen-18, deuterium and tritium in the water cycle.

1971-81 Assistant, then senior assistant at Physics Institute, University of Bern.

1981 Lektor, Physics Institute, University of Bern.

1983 Privatdozent, University of Bern.

1990 Associate Professor (nebenamtlicher Extraordinarius) for experimental physics, University of Bern.

1993 Elected as a Fellow of the American Geophysical Union.

Uli also spent time at:

Geoscience Group, Weizmann Institute, Rehovot, Israel;

Institute for Environmental Physics, Heidelberg, FRG;

Atmospheric and Oceanic Sciences Program, Princeton University.

Among the various committees and boards on which Uli served are

- International Commission on Atmospheric Chemistry and Global Pollution (1985-1990);
- Comité Scientifique du PNEDC (Programme National pour l'Etude de la Dynamique du Climat; French climate research programme)
- Expert for German Climate Research Programme (1990);
- International Scientific Steering Committee for JGOFS (Joint Global Ocean Flux Study);
- Chairman, Swiss National SCOPE Committee;
- Swiss National IGBP Committee;
- Eidg. Kommission Nukleare Entsorgung (Swiss Federal Commission on Nuclear Waste Disposal);
- Vorstand (committee) Bernische Naturforschende Gesellschaft;
- The advisory boards for Tellus B, Climate Dynamics, Radiocarbon.

His own description of his research activities was:

- Modelling of the global carbon cycle, in particular of the role of the ocean: anthropogenic CO₂ increase and isotopic perturbations (¹³C, ¹⁴C) due to human activities, natural perturbations of the carbon cycle (glacial-interglacial CO₂ variations; ¹⁴C variations),
3-dimensional modelling of the oceanic carbon cycle (with J. Sarmiento, Princeton);
- Greenhouse effect and climatic change;
- Build-up and supervision of a stable isotope laboratory for measuring ¹⁸O/¹⁶O, ¹³C/¹²C and (since 1990) ¹⁵N/¹⁴N in the environment;
- Experimental studies of the carbon cycle by means of stable isotope analyses: studies on concentration and isotopic composition of CO₂ in atmosphere and soils, dependence of ¹³C/¹²C fractionation of plants on environmental stress (ozone; water), in collaboration with botanists, stable isotopes in CO₂ from old polar ice cores as a constraint on the cause of glacial-postglacial CO₂ concentration variations;
- Palaeoclimate studies: rapid variations in the late glacial (Younger Dryas) as recorded in stable isotopes in lake sediments; stable isotopes in tree rings as climate records;
- Use of isotopes (tritium, ¹⁸O/¹⁶O) in hydrology: determination of age and origin of groundwater (till about 1983); stable isotopes in the atmospheric water cycle.

His university teaching included both introductory physics, atomic physics and advanced courses in a range of aspects of environmental physics.

Those of us in the carbon cycle community will appreciate the importance of Uli's work. For the work presented in this report, two items have proved to be key contributions:

- The box-diffusion model work from 1975. This is still used widely and it forms the basis of several of the model calculations presented in this report.
- The pioneering inversion calculation (Siegenthaler and Oeschger, 1987) in which the inverse calculations were used to deduce terrestrial fluxes from the CO₂ concentrations measured in ice-cores.

Uli leaves a wife and two children.

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