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

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Abstract

Various projections of the relation between future CO_2 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 CO_2 concentrations resulting from specified emission scenarios, (ii) inverse calculations determining the emission rates that would be required to achieve stabilisation of CO_2 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 CO_2 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 CO_2 and climate. The uncertainties in such feedbacks are too large to justify defining any standard cases for comparitive 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 CO_2. 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 CO_2 concentrations as functions of time, that lead to constant CO_2 concentrations in the 21st or 22nd centuries.

Previously, projections of future CO_2 had been included in the IPCC reports (IPCC 1990, 1992). The update (IPCC, 1992) included few specific projections of CO_2. 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.

2. Carbon Budget Issues

2a Budget issues

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

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

where:
$C(t)$ is the atmospheric CO_2 concentration (in ppmv relative to dry air),
$Q_{\text{foss}}(t)$ is the 'fossil' emission rate, including both combustion of fossil fuel and CO_2 emissions from cement production. The IPCC (1990, 1992) reports used the term 'industrial' for this component,
$D_{\text{n}}(t)$ is the net carbon flux from land-use change (including delayed effects from past land-use changes),

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

Processed December 3, 1994

$S_{\rm ocean}(t)$ is the net carbon uptake by the oceans,
$S_{\rm fert}(t)$ is the net flux associated with CO_2-enhanced growth,
$S_{\rm resid}(t)$ 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 $S_{\rm resid}(t)$) refer either to anthropogenic forcing ($Q_{\rm foss}(t)$ and $D_{\rm n}(t)$) or to the natural response to such forcing ($\frac{d}{dt}C$, $S_{\rm ocean}(t)$, $S_{\rm fert}(t)$). 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 CO_2. Multi-year averaging can also remove some of the short-term climatic variability that we have assigned to the term $S_{\rm resid}(t)$.

3. The standard cases defined in the instructions assume that the residual 'missing-sink' term, $S_{\rm resid}(t)$, 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 CO_2 partial pressure data and (to a lesser extent) when interpreting inversions of spatial distributions of CO_2.

'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 CO_2. 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 CO_2 levels. In principle, anthropogenic emissions ought to include any changes in CO_2 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 CO_2, the vast majority of these are quickly oxidised to CO_2. For global averages, on time-scales of years, the atmospheric carbon budget is what determines the rate of increase of CO_2.

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 CO_2. 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 CO_2 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 CO_2 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 CO_2 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.

Foward 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, $Q_{\rm foss}$, and the **net** carbon flux from land-use-change, $D_{\rm n}$. Section 9 exploits this representation by expressing it in a response function form (valid for the linear regime) as

$$N_{\rm a}(t) = 2.123[C(t) - C_0] = \int_0^\infty G_{\rm a}(\tau)\, Q(t-\tau)\, d\tau \qquad (3.1)$$

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

$$Q(t) = Q_{\rm foss}(t) + D_{\rm n}(t) \qquad (3.2)$$

and the atmospheric response function $G_{\rm a}$ represents the combined 'natural' response: oceanic and biotic. (The response function $G_{\rm a}$ 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, $Q_{\rm foss}(t)$, obtained by assuming a specified land-use component $D_{\rm n}(t)$. 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 ^{3}H 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)
^{3}H (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 $\mathrm{m^2 y^{-1}}$.

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 CO_2-enhanced growth. The reservoir turnover times also affect the response to perturbations in the isotopic composition of atmospheric CO_2. Thus, isotopic data provide some validation of reservoir turn-over times. In particular, ^{14}C 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 CO_2 concentration since this will ultimately limit the ability of terrestrial systems to store additional carbon.

Appendix A suggests three forms of dependence:

Linear

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

Logarithmic

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

and Hyperbolic

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

where $C(0)$ is an initial reference concentration and the β_j are non-dimensional values of the sensitivity of NPP to CO_2. 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 $D_{\rm n}$ could be incorporated into the carbon cycle model rather than being used to define $D_{\rm n}$ 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 CO_2. (e.g. The Global Change Institute on the Global Carbon Cycle, Snowmass Village, July 1993, and The Fourth International CO_2 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 CO_2 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 ^{14}C constraint on oceanic CO_2 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.

4. Strategies for Achieving Carbon Balance

The atmospheric carbon balance, with the assumption that CO_2-fertilisation accounts for all the 'missing sink', is expressed as:

$$2.123\frac{d}{dt}C(t) = Q_{\mathrm{foss}}(t) + D_{\mathrm{n}}(t) - S_{\mathrm{ocean}}(t) - S_{\mathrm{fert}}(t) \tag{4.1}$$

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 $Q_{\mathrm{foss}}(t)$, $D_{\mathrm{n}}(t)$ exactly as specified, with $S_{\mathrm{ocean}}(t)$ calculated (possibly using a ^{14}C calibration) and $S_{\mathrm{fert}}(t)$ 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 $Q_{\mathrm{foss}}(t)$ and calculated $S_{\mathrm{fert}}(t)$ and $S_{\mathrm{ocean}}(t)$ and track the prescribed $C(t)$ in order to deduce $D_{\mathrm{n}}(t)$. The model parameters are to be tuned to give $\bar{D}_{\mathrm{n}} = 1.6$ 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 $Q_{\rm foss}(t)$ and $C(t)$, either of which can be used to determine the other. Calculations of both types are requested in the instructions.

The prescribed CO_2 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 $\bar{Q}_{\rm foss} = 5.45$ GtC/yr and $\bar{D}_{\rm n} = 1.58$ GtC/yr. In terms of the atmospheric budget shown in equation (4.1), this constrains the sum of oceanic and fertilisation fluxes to be $S_{\rm ocean} + \bar{S}_{\rm fert} = 3.65$ or more generally $S_{\rm ocean} + \bar{S}_{\rm fert} = 2.07 + \bar{D}_{\rm n}$. This is shown diagramatically 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.

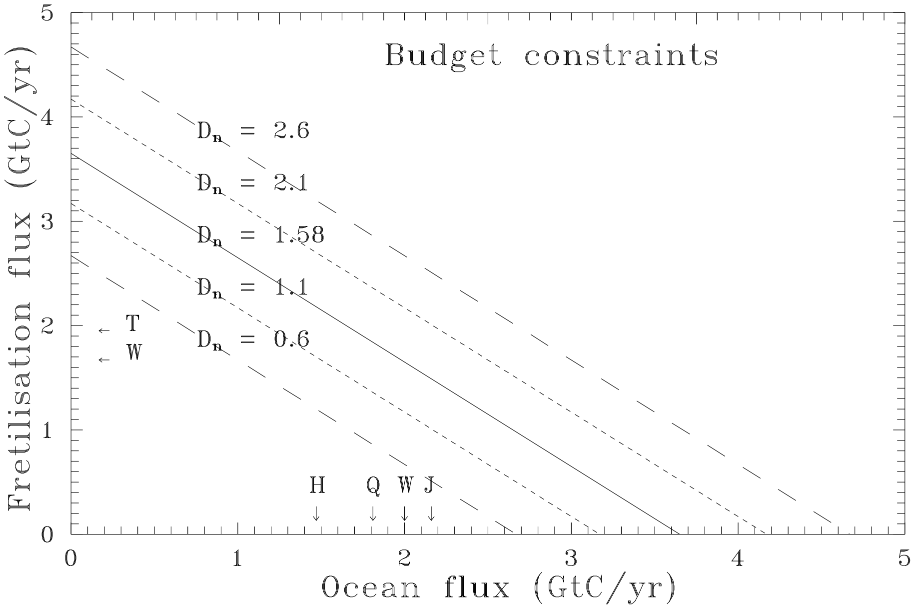

Figure 4.1. Relation between components of the atmospheric carbon budget averaged over 1980–89. The lines for various mean 'land-use' fluxes specify the combinations of ocean flux and fertilisation flux that are compatible with a balanced atmospheric budget. Labelled points along the axes show fluxes 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.

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 CO_2-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 A_1 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 A_2, 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 CO_2 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 A_1, E, H, J, L, M, Q, R and W. Models R^* and T [1] 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 CO_2 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.

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.

[1] Information provided about feedbacks in Model T was ambiguous.

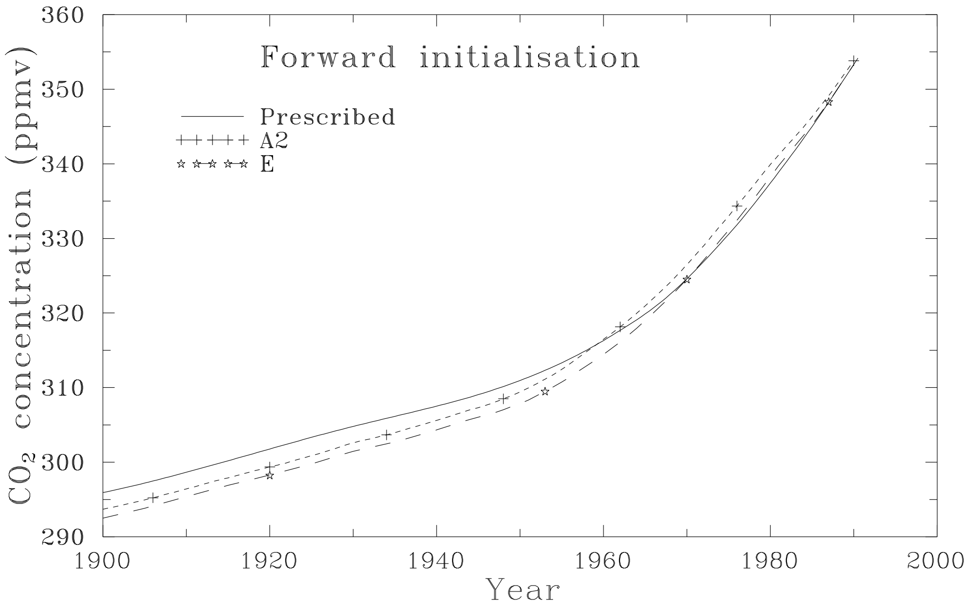

Figure 6.1. Calculated concentrations for models with forward initialisation.

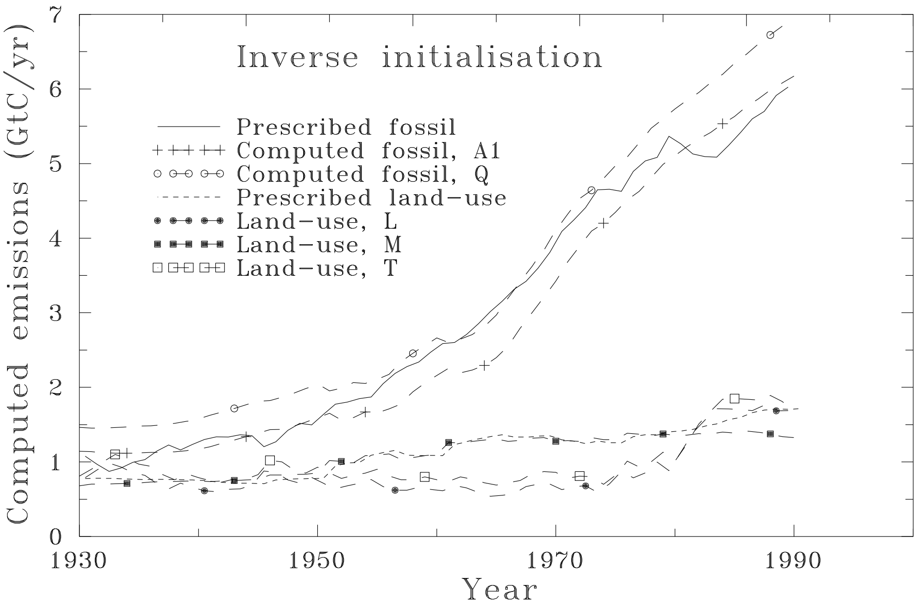

Figure 6.2. Calculated emissions for models with inverse initialisations, compared to prescribed functions. There are two groups, depending on whether the fossil or the land-use component was deduced in the inversion.

	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.

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 CO_2 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 CO_2 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 CO_2 unless these biotic processes actually change.

The radioactive isotope ^{14}C plays a key role in the calibration and validation of ocean carbon models. Two aspects of the ^{14}C distribution are important: the natural distribution, in which different ^{14}C levels reflect the effect of radioactive decay (half-life 5730 years) and the excess ^{14}C from nuclear testing when atmospheric ^{14}C levels almost doubled in the early 1960s. Extensive data sets of oceanic ^{14}C 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.

^{14}C data play a small role in validating models of terrestrial carbon. As noted above, ^{14}C data have been used to estimate turn-over times for soil carbon. One important use of terrestrial ^{14}C data is as a proxy for atmospheric ^{14}C in determining the Suess effect (i.e., the decline in the proportion of atmospheric ^{14}C due to dilution of the atmospheric reservoir by CO_2 derived from fossil sources in which all the ^{14}C has decayed).

The use of bomb-^{14}C poses some difficulties because the sources are poorly known, due to military secrecy. The usual way of using bomb-^{14}C in carbon cycle models is to specify the atmospheric ^{14}C levels from observations. For the present exercise, specified ^{14}C levels were provided. These are plotted in Figure B.5. To make best use of such data, the ^{14}C 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 therafter, to check that the decline in atmospheric ^{14}C levels matched observations. Enting and Lassey (1993) addressed this problem by performing the ^{14}C calculations in 'forward' mode throughout, with a 'bomb-^{14}C production factor' to take account of source uncertainty and tuned to match observations. Some aspects of the ^{14}C calibration issue are analysed by Enting (1990).

In analysing oceanic ^{14}C data, it has become common to use the penetration depth $z_{\rm pen}$ 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	ΔTotal $50-73$	ΔMixed $50-73$	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 anlysis of the ^{14}C budget. This result requires further analysis.