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_{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, $Q_{\mathrm{foss}}(t)$, obtained by assuming a specified land-use component $D_{\mathrm{n}}(t)$. 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 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 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

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

and Hyperbolic

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

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_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 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.

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