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^*	Alcomo 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):

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

where M is the biomass, ϕ is the proportion of photosynthesis lost in respiration, and $M(t_0)$ and $\mathrm{NPP}(t_0)$ are tuned to reproduce the present-day biosphere. GPP is the Gross Primary Productivity (photosynthesis) and m is the maintainance 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, $K = 7685$ m^2/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.
CO_2-fertilisation. The NPP is taken as linear in atmospheric CO_2 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 CO_2 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:

$$\frac{d}{dt}C(t) = 0.471 m_2 Q_{\text{foss}}(t) - m_3 C(t) \tag{C.C.1}$$

with m_3 fixed at 0.001 to represent variations on millenial time scales and m_2 fitted by a regression fit of ice-core CO_2 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 CO_2 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 $(m_3 C(t-1))$ 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 achived 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 $D_{\rm n}$ 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, F_2

Name: SLAVE
Description: **S**cheme for **L**arge-scale **A**tmosphere- **V**egetation **E**xchange
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 F_2.
Terrestrial: Nine vegetation types on 5 degree by 5 degree grid. The model has five submodels: vegetation, soil water, carbon, nutrient and CO_2-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 CO_2 for version F, and hyperbolic dependence on CO_2 for version F_2. 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 F_2.

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 CO_2 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 CO_2 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 CO_2 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 molC m^{-2} yr^{-1}. This results in a global model bomb-^{14}C uptake of 9.27×10^9 atoms cm^{-2} as compared to the observed 8.4×10^9 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 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

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

with

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

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 a l'Energie 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 CO_2 employs the OPA (Océan Parallelisé) 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 CO_2 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 CO_2 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 ^{3}H and bomb ^{14}C, and other validations are under preparation, including simulations for natural ^{14}C.

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_{CO2} 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:

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

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

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

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 particluar: 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 CO_2.
Terrestrial: Six box representation. Fertilisation has logarithmic dependence on CO_2 concentration. Some of the rates are temperature dependent in the standard form of the model.
Other: CO_2-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

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

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 CO_2 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 CO_2 concentration history, or a forward calculation with specified net deforestation, and obtaining a best fit to the CO_2 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:

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

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

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

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/m^3/atm, ocean area, $A_s = 3.63 \times 10^{14}$ m^2, and mixed layer P_{CO2}, 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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