Appendix A: Instructions for Calculations

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

Carbon Cycle Model Calculations for the IPCC

Working Group 1 of IPCC is seeking calculations relating future atmospheric CO_2 concentrations to emissions, particularly for cases involving possible stabilization of concentrations [1]. At a joint meeting of the IPCC WG1 Bureau and the Chairs of the International Ozone Assessment Panel (Bath, U.K., 18–19 February 1993) Tom Wigley and Ian Enting were charged with the responsibility of convening and coordinating this activity. We are seeking participation from carbon cycle modelling groups world-wide.

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

Contents

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

Processed November 25, 1994

(Contacted addresses deleted)

Acknowledgements: The coordinators acknowledge valuable comments from Uli Siegenthaler, Martin Heimann and Mike Oppenheimer.

A.1. Summary of calculations required.

A.1a. General

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

A.1b. Standard integrations

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

Essential

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

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

Highly desirable

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

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

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

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

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

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

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

Desirable

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

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

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

Possibly useful

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

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

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

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

A.1c. Specifications for standard cases

- From 1990 onwards, all standard cases use specified net flux from land-use change, calculate any fluxes from CO_2 fertilization and, depending on which case is considered, either deduce industrial emissions [3] from specified concentrations *(inverse)* or calculate concentrations from specified industrial emissions *(forward)*.
- The future net flux from land-use change is described in Note A.6.E. Forward integrations of the IS92a–f industrial sources should use the IPCC 1992 deforestation scenarios for 2000 to 2100 as given. All other cases should use the modified IS92a (i.e. IS92a* from Table 4 of Note A.6.E) which goes to zero at 2100 and remains zero. All cases should use linear interpolation over 1990 to 2000 to connect the land-use flux used in the initialization phase with whichever case is used after 2000.
- For the effect of land-use change pre-1990, the net flux from Houghton is provided as an option (Note A.6.A). If some alternative is used then the net flux from land-use change should be 1.6 Gt C y^{-1} averaged over 1980–89 inclusive (except in the sensitivity studies). This is the IPCC (1990) 'best guess' value and is close to the estimates by Houghton.
- The atmospheric CO_2 concentration should agree as well as possible with the supplied fit to the observational record. If the period 1765 to 1990 is treated with inverse modelling, then the supplied concentration record should be used.

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

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

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

- The rate of increase of atmospheric CO_2 should be fixed at 1.7 ppmv y^{-1} for mid-1990 (i.e. $t = 1990.5$), except in sensitivity studies. (See Note A.6.C). For inverse calculations from 1990 onwards (i.e. the stabilization cases), the 1990 concentration needs to be fixed at the starting value of the prescribed time series. We specify 354.17 ppmv for mid-1990.
- The calculation of the impulse response should be as a perturbation from pre-industrial equilibrium with concentration 278 ppmv (with perturbation from S650 as an optional extra). The input should be 10 Gt C over 1 year. For the perturbation case, the 10 Gt should be released during 1995. The integrations should be for 200 years or preferably 500.
- Recommended constants: 1 ppmv = 2.123 Gt C in atmosphere; ocean area = 3.62×10^{14} m^2.

A.1d. Output

Essential

i: Fossil carbon emissions (in gigatonnes per year) and CO_2 concentrations (in ppmv) for each case considered, for the period 1765 to 2100.

ii: Contents of terrestrial biosphere reservoirs (annual data in Gt C) and fluxes between reservoirs (in Gt C y^{-1}), especially atmosphere-to-ocean and atmosphere-to-terrestrial-biosphere.

Desirable

iii: Mixed layer ^{14}C, as $\Delta^{14}C$ in ‰.

iv: Ocean ^{14}C inventory for 1/1/74 and preferably over the period 1940–1990. Given as excess ^{14}C atoms per square meter.

v: Results as described above extended to 2200 or beyond.

Further details are given in Section A.2.

A.1e. Sensitivity studies

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

i: Explore sensitivity to fixing the rate of concentration increase to the mid-1990 value of 1.7 ppmv y^{-1}.

ii: Explore sensitivity to fixing net flux from land-use change at an average of 1.6 Gt C y^{-1} over 1980–90. We suggest using 0.6 and 2.6 Gt C y^{-1}.

iii: Compare calculations with two different forms of CO_2-enhanced production:
(a): Growth logarithmic $\propto [1 + \beta \ln(C/C_0)]$, *(b)*: Saturation $\propto G_\infty \frac{C-C_c}{C+b}$ with $C_c = 80$ ppmv and the constraint $G_\infty = (C_0 + b)/(C_0 - C_c)$ and b used for tuning. (see Allen et al. *Global Biogeochemical Cycles, 1*, p1).

A.1f. Data provided

i: $C(t)$ 1765 to 1990. For input to inverse calculations and fitting in forward cases.

ii: $C(t)$ for 1990 to 2200 for the stabilization cases. (7 cases)

iii: Fossil carbon emissions for 1844–1990.

iv: Atmospheric ^{14}C for 1800 to 1990 for cases with ^{14}C forced to track atmospheric levels.

v: Net release from land-use change, $D_n(t)$ from Houghton.

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

A.2. Deliverables

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

To aid in the interpretation of the results (inter-model differences), other output items are desirable. In particular, 1765-to-end-year annual time series of total terrestrial biomass and flux into the ocean will allow the full budget, and its changes, to be assessed for each model. A breakdown of terrestrial biomass changes into components (above-ground living biomass, litter, soil carbon, etc.) is also desirable, as are gross fluxes, if possible.

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

Line 1: Integers N and M

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

Lines $N+2$ to $M+N+1$: Output records.
The items in the record should by separated by blanks and in floating point format, i.e. suitable for reading by Fortran or Pascal free format reads to real variables. We suggest that the first few items should be

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

CO_2 concentration In ppmv, suggest 2 decimal places.

Fossil carbon emissions in Gt C y^{-1}. Suggest at least 2 decimal places.

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

Time As above.

Atmospheric ^{14}C As Δ^{14}C in ‰.

Mixed layer ^{14}C As Δ^{14}C in ‰.

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

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

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

A.3. Background

A.3a. The choice of integrations

Working Group 1 of IPCC is seeking calculations of future CO_2 levels, particularly those related to possible stabilization of concentrations. Article 2 of the Climate Convention states that the ''ultimate aim'' of the Convention is

"...to achieve stabilization of greenhouse gas concentrations ...at a level that would prevent dangerous anthropogenic interference with the climate system ...within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner"

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

At the eighth session of the IPCC (Harare, Zimbabwe, 11–13 November 1992) it was agreed that the deliverables under the 1993–95 workplan of WG1 do not include calculations of the climate implications of the 1992 IPCC emissions scenarios developed by Leggett et al. (1992). Nor will these scenarios be revised [1]. Thus, IPCC WG1 has no remit to pursue the CO_2 concentration implications of the IPCC92 scenarios [2]. Nevertheless, since such calculations are likely to assist in interpreting the results of stabilization experiments, they are included in the optional part of the present exercise.

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

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

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

The 'science' cases (DEC0%, DEC1%, DEC2%) These cases with specified percentage reductions in industrial carbon releases, allow direct comparison of model differences

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

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

using concentrations from forward calculations. In many contexts, forward calculations are easier to explain.

The 'delayed' cases (DS450, DS550 [1]) These provide alternative pathways to stabilization that may be more realistic, given the difficulties of achieving stabilization, and at any rate provide cases for assessing the implications of delay.

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

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

A.3b. The basis of technical specifications

Our principal requirements are that **models should produce an acceptable fit to the record of CO_2 concentrations over the industrial period, and that models should treat processes in the past and future in an equivalent manner.** We also require that the components of the model's carbon budget should lie within the recognized uncertainties in the observed carbon budget.

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

In choosing the modelling strategy modellers should consider

- The fact that the atmospheric CO_2 history is better known than most other components.
- The important role of ^{14}C in constraining ocean carbon uptake.

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

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

A.4. Data sets prescribed

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

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

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

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

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

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

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

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

A.5. Reporting and model comparison process

In order to enhance communication for the exercise we have set up an *anonymous ftp* area at CSIRO [1]. This will contain data files, news, utility programs, etc.

To access it, the procedure *with user input typed like this* and **machine prompts in bold** is:
normal prompt *ftp ftp@dar.csiro.au*
ftp> Name: *ftp* or *anonymous*
password Type your e-mail address
ftp> *cd IPCC*
ftp> *ascii*
ftp> *get filename* using actual filenames. This can be repeated as required.
ftp> *quit*

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

All participants will be kept informed of progress as this exercise proceeds. There will be an opportunity to discuss results at the Global Change Institute in Snowmass, Colorado (July 18–30, 1993), to which many modellers have been invited. However, the main venue for discussing results will be at a special IPCC Working Group 1 meeting on 18 September, 1993, following the Fourth International CO_2 Conference in Carqueiranne, France.

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

An overall assessment of the modelling exercise will form part of the carbon cycle chapter (lead authors D. Schimel, T. Wigley, D. Alves, M. Heimann, U. Siegenthaler, I. Enting [2]) of the 1995 IPCC WG1 assessment.

A.6. Technical notes:

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

Since Houghton's published land-use emissions data begin in 1850 (see Table A.1) and since the extrapolated industrial emissions begin in 1844, forward calculations will give constant concentrations over 1765–1843. We can, however, be quite confident that concentration levels increased over this period. While there is weak evidence that some of this increase

[1] The description of ftp is the current access mode. The original instructions described an earlier form.
[2] D. Raynaud was added when Uli Siegenthaler became ill.

may have been part of a natural fluctuation, possibly associated with the Little Ice Age, in order to ensure comparibility our standard case ignores this possibility.

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

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

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

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

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

Technical note A.6.C: Avoiding emission discontinuities

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

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

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

Technical note A.6.D: Iterative inverse calculations

Because the primary IPCC interest is in CO_2 stabilization [1], many of the calculations are inverse calculations with input specified in terms of prescribed concentrations. While some models can perform such inverse calculations within the integration procedure, in other cases it will be necessary to use an iterative technique, starting with an approximate source and successively refining it to minimize the differences between calculated and prescribed concentrations. Further information is available from Tom Wigley.

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

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

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

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

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

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

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

• The values from Table A.4 should be linearly interpolated as required for the period 1991 onwards. (In particular, the 1990 industrial release should be the value from Marland).

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

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

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

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

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

The primary calculations are those related to the objectives of the Climate Convention, i.e., concentration stabilization. Since no particular stabilization level has been specified, we must consider a range of possibilities. We could use multiples of the pre-industrial level (e.g., 1.5, 2.0, 2.5 times) or specific 'round number' values. The fact that the users of the results (policy advisors and makers) are more likely to 'understand' round numbers leads us to choose the latter. The stabilization levels we have chosen are 450 and 650 ppmv (concentration scenarios S450 and S650). Both of these levels would likely require new policies to limit

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

CO_2 emissions. The lower value is probably below the limit of realistic attainability and even the upper value represents a substantial concentration reduction below what might be expected under the central IPCC92 ‘existing policies’ scenario (IS92a).

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

There is no simple set of analytical expressions that satisfy all of the above conditions. We have therefore constructed the future $C(t)$ scenarios graphically, modifying our initial projections slightly after running some preliminary inverse calculations to ensure that the output emissions were sensible[1]. These $C(t)$ scenarios will be provided as annual values on floppy disk.

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

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

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

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

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

Appendix B: Data Sets Provided

Prescribed data files

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

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

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

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

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

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

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

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

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

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

stab.dat: Prescribed CO_2 concentrations for the 7 stabilisation scenarios. Half-year intervals.

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

Further details

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

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

To ensure smoothness at all times, the pre-1990 and post-1990 segments of the CO_2 history were represented by differentiable functions: smoothing splines pre-1990 and Padé approximants (ratios of polynomials) post-1990.

Past

The CO_2 concentrations for the period 1765 to 1990 were specified as values every six months. These values were a smoothed representation of the combination of direct observations from Mauna Loa (Keeling et al., 1989) and ice-core data from Neftel et al. (1985) and Friedli et al. (1986).

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

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

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

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

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

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

The specifications used for each are:

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

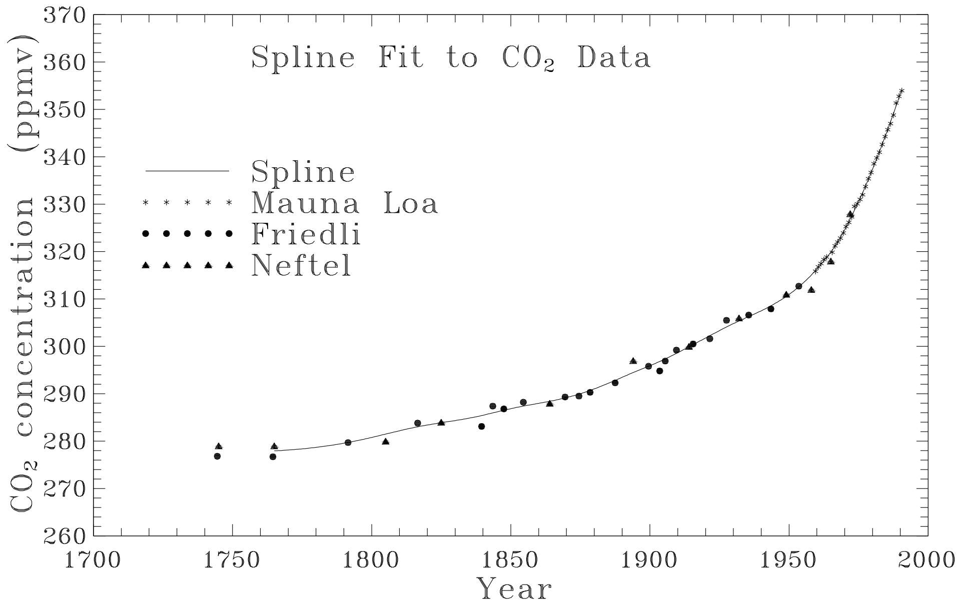

Figure B.1. Spline fit defining prescribed CO_2 concentrations from pre-industrial times to the present, compared to observed concentrations from ice-cores and direct atmospheric measurements.

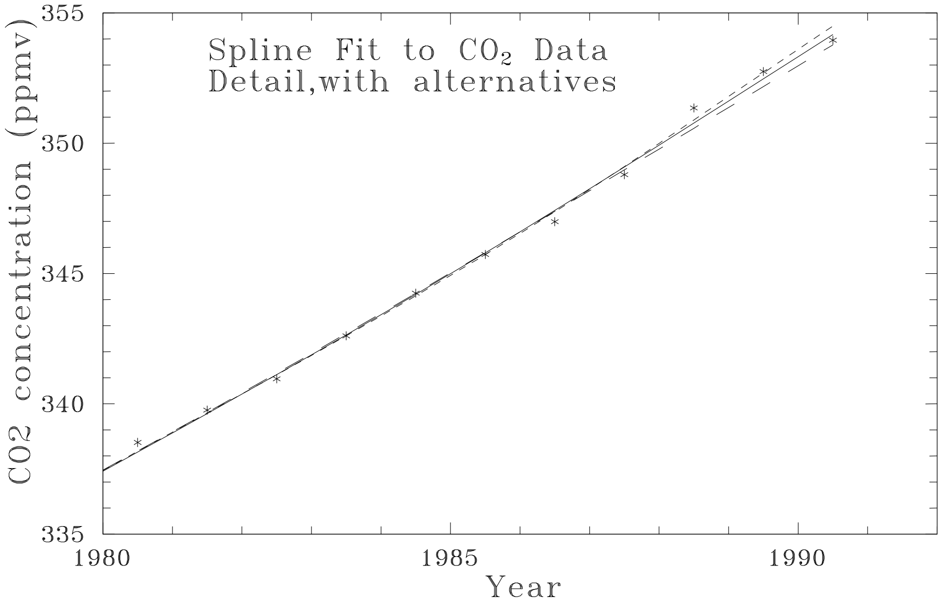

Figure B.2. Prescribed spline fits to CO_2 data showing detail of the period immediately prior to 1990. The standard case is the solid line. The other cases are those defined for sensitivity studies.

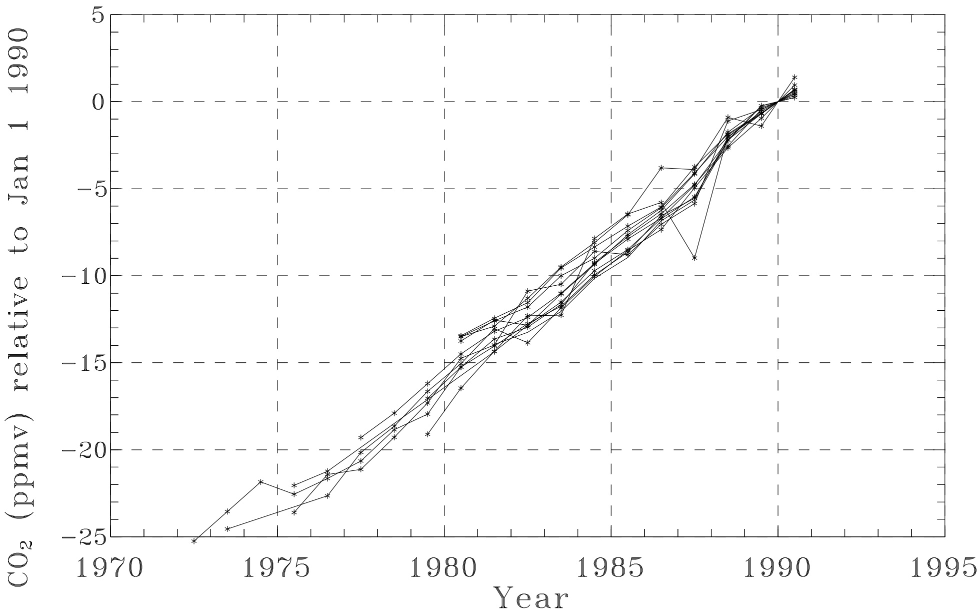

Figure B.3. Growth in atmospheric CO_2 over the 1980s. Annual means of data from CDIAC (1991), normalised to 1989–90 mean.

Figure B.1 shows the preferred spline fit over the period 1765 to 1990. The alternatives are barely distinguishable on this scale. Figure B.2 shows the three splines over the period 1975 to 1990 compared to the data. The question of which curve is the best fit depends on the interpretation that is placed on the CO_2 data. We regard 1988 and 1989 as being anomalously high in CO_2 concentration. The atmospheric δ^{13}C for this period is also anomalous (R. Francey, personal communication). The alternative would be to regard 1990 as anomalously low. There is scope for using later data to resolve the question.

In view of the importance of the rate of growth in atmospheric CO_2, we show additional data to justify our use of the Mauna Loa record for defining the specified atmospheric CO_2 concentration prior to 1990. Figure B.3 shows data from CDIAC (1991) demonstrating the rate of increase over the 1980s. The data plotted are annual means, normalised to a common 1989–90 mean of zero. It will be seen that the range 1.6 ± 0.1 ppmv y^{-1} is representative of this data set which includes all stations for which data were available over all or most of the decade. As noted in Section 3, a more recent analysis by the NOAA group suggests 1.53 ppmv y^{-1} as the best estimate of the mean rate of increase over the 1980s. The NOAA estimate effectively weights the data set to take account of the fact that tropical sites are under-represented (as a proportion of the earth's area) in the NOAA network.

Future

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

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

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

with

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

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

Three distinct cases were used:

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

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

Table B.1. Specification of Padé approximants used to define the CO_2 concentration histories prior to stabilisation. Here $c(t)$ is the concentration and $d(t)$ is the trend.

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

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

Radiocarbon data for validation

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

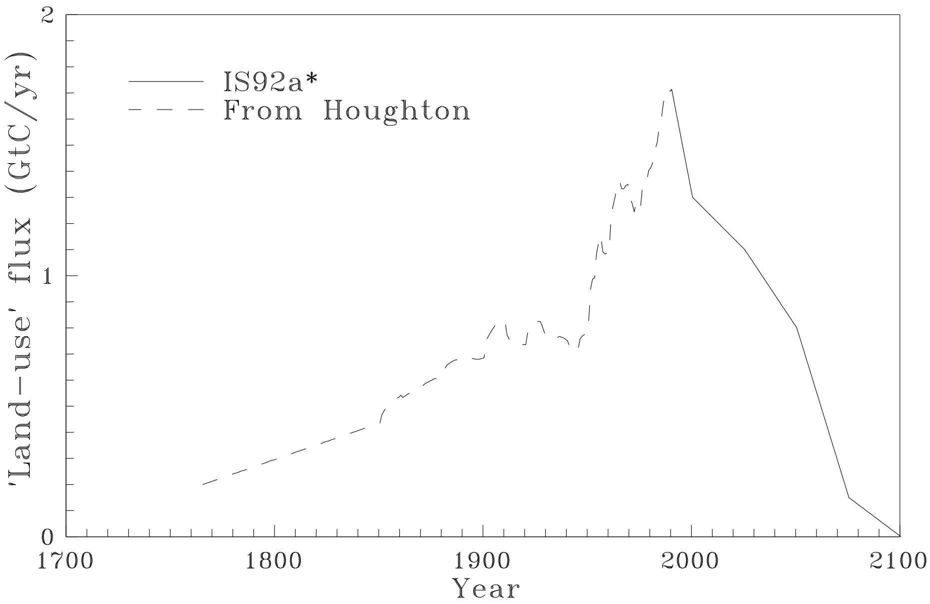

Figure B.4. Prescribed net carbon flux from 'land-use' changes.

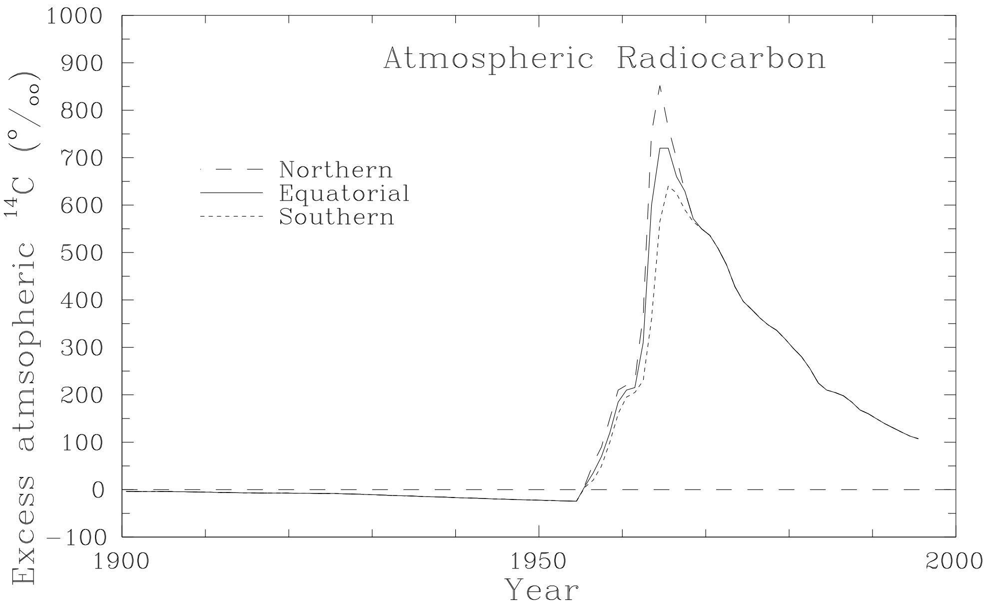

Figure B.5. Atmospheric ^{14}C levels prescribed for validation calculations.