

Modelling Earth System Change: I. Validating Parameterisations for Attribution Calculations

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Abstract

This paper describes a set of analyses to validate simple model parameterisations as part of a model assessment for calculations attributing global change to particular groups of emissions. The report also identifies issues involved for the assessment to address the recommendations from the SBSTA experts' meeting (Bonn, May 2001). **DISCLAIMER:** The scenarios for future emissions used in this report were chosen to provide a standard case for the various models in the intercomparison. This case should not be treated as having any special status as a likely future. In particular, it should be noted that the SRES A2-marker case is predicated on a global population of around 15 billion in 2100.

1 Introduction

This report documents a set of standardised calculations that are intended as validation of simple parameterised models of global change.

The assessment for which the present study was undertaken, arose from a proposal from Brazil to set emission targets on the basis of historical responsibility for global change. The proposal was presented to the Ad Hoc Group on the Berlin Mandate (AGBM) and subsequently referred to the SBSTA. A summary of the formal consideration within the FCCC process (through to 2001) is given by Enting and Law (2002) (see also SBSTA, 2001).

Our modelling of global change using parameterised models is part of an on-going research activity in CSIRO (Australia). The methodology involves developing highly-modularised models so that we can, as desired, investigate particular aspects of global change, using detailed modelling of individual system components with inputs and/or outputs from/to less detailed representations of other components of the earth system. The present report is intended as the first in a series of CSIRO Atmospheric Research Technical Papers with the common title: *Modelling Earth System Change* and numbered I, II, etc. in addition to the CAR Technical paper numbers.

The SBSTA intercomparison involved the following components:

- A ‘reference’ case, supplied by SBSTA, based mainly on analyses with the Hadley Centre HadCM3 model.
- A default case, comprising a set of standard inputs (emissions of CO₂, CH₄ and N₂O; direct and indirect radiative forcing for aerosols) and a set of standard parameterisations for: the dependence of concentrations on emissions, the dependence for forcing on concentration and the dependence of temperature (and sea-level) on forcing.
- A comparison between this default case and the reference case, to test that simple parameterisations could reproduce the behaviour of complex models. To the extent that the default is fully specified, all modelling groups that use the default should obtain identical results (to numerical accuracy). There are however, a few details that were not specified in the default case. These are noted in the description below.
- Similar comparisons with alternative parameterisations using either the same inputs as the default case or alternative estimates.

The layout of the remainder of this report is as follows. Section 2 describes the ‘default’ case. Section 3 describes various extensions that we consider for CO₂. Section 4 describes the other gas concentrations. Section 5 describes the validation of the climate change variables. Section 6 revisits these various results, relating changes to time of emission.

2 Default parameterisations

For the purposes of intercomparison of models, a number of standard representations have been defined. These are:

- standard forcings, expressed as emissions, concentrations or radiative forcing, depending on the constituent;
- standard default responses of particular components of the earth system.

The present section describes these standard cases. Modellers who use all the default responses should (to within numerical accuracy) all obtain the same results, apart from small differences due to some aspects of the default being left unspecified. Of course, the aim of the assessment is to determine the extent to which the results differ when different parameterisations are used.

Inputs:

Past CO₂ emissions From CDIAC, as sum of fossil carbon emissions (Marland et al., 2001) and emissions from land-use change (Houghton, 1999; Houghton and Hackler, 2000).

Past CH₄ emissions From EDGAR-HYDE data set (Aardenne et al., 2001).

Past N₂O emissions From EDGAR-HYDE data set (Aardenne et al., 2001).

Future CO₂ emissions SRES A2-marker scenario. (Nakićenović et al, 2000: p471).

Future CH₄ emissions SRES A2-marker scenario (Nakićenović et al, 2000: p471).

Future N₂O emissions SRES A2-marker scenario (Nakićenović et al, 2000: p471).

Direct radiative forcing of aerosols Prescribed function from SRES A2-marker scenario, see Figure 2.

Indirect radiative forcing of aerosols Prescribed function from SRES A2-marker scenario, see Figure 2.

The emission estimates and scenarios are presented as annual values for specific years. For computational convenience, these are actually used as instantaneous values in the middle of the year, with linear interpolation used for other times.

Model relations:

CO₂ concentrations Perturbation from pre-industrial concentration of 280 ppm. Response given by Bern model expression, equation (2.1).

CH₄ concentrations Perturbation from pre-industrial concentration of 700 ppb; fixed 8.4 year lifetime; (Prather et al., 2001: Table 4.1).

N₂O concentrations Perturbation from pre-industrial concentration of 275ppm; fixed 120 year lifetime; (Prather et al., 2001: Table 4.1).

Radiative forcing of gases Functional relations from the IPCC Third Assessment Report, (equations 2.4a–h).

Warming Response function from HadCM3, equation (2.5a).

Sea level rise Response function from HadCM3, equation (2.6a).

The forcing, warming and sea-level rise are all expressed as differences from pre-industrial conditions. The emissions are the anthropogenic inputs that have caused these changes. Therefore the concentrations calculated using the response functions are perturbations from pre-industrial. Comparisons with observed concentrations will require specification of the pre-industrial value. The default calculations use the values specified above, which are taken from the IPCC Third Assessment Report.

These default specifications can be summarised as:

Component	Emissions	Concentrations	Forcing
CO ₂	CDIAC	280 ppm + Bern response	Eq. 2.4c
CH ₄	EDGAR-HYDE	700 ppb + 8.4 yr lifetime	2.4d
N ₂ O	EDGAR-HYDE	275 ppb + 120 yr lifetime	2.4e
aerosol (direct)	—	—	prescribed
aerosol (indirect)	—	—	prescribed
halocarbons	—	—	—

The default response for CO₂ is the Bern model response from the Third Assessment Report, expressed as

$$R_{\text{Bern:TAR}}(t) = 0.152 + 0.253 \exp(-t/171.0) + 0.279 \exp(-t/18.0) + 0.316 \exp(-t/2.57) \quad (2.1)$$

The gas response functions are defined to have $R(0) = 1$, and so must be used with a scale factor, giving

$$C_{\text{CO}_2}(t) = C_{\text{CO}_2:\text{eqm}} + A_{\text{CO}_2} \int_{t_0}^t R(t-t') E_{\text{CO}_2}(t') dt' \quad (2.2)$$

where the factors A_η define the conversion from emission units (generally in terms of masses) to gas units (usually mixing ratios).

For gases that can be characterised by a single lifetime, τ_η , we have

$$R_\eta = \exp(-t/\tau_\eta) \quad (2.3)$$

Our calculations work in the units used for the emissions: Pg carbon (Gt C) for CO₂; Tg CH₄ (Mt CH₄) for CH₄; Tg N (Mt N) for N₂O. These are the units generally used in IPCC reports. Note that the EDGAR-HYDE CH₄ emissions are in Tg C y⁻¹, not Tg CH₄ y⁻¹ (van Aardenne et al., 2001).

We use the conversion factors:

$$\begin{aligned} A_{\text{CO}_2} &= 0.471 \quad \text{ppm}/(\text{Pg C}) \quad \text{ppm}/(\text{Gt C}) \\ A_{\text{CH}_4} &= \frac{12}{16} A_{\text{CO}_2} \quad \text{ppb}/(\text{Tg CH}_4) \quad \text{ppb}/(\text{MtCH}_4) \\ A_{\text{N}_2\text{O}} &= \frac{12}{28} A_{\text{CO}_2} \quad \text{ppb}/(\text{Tg N}) \quad \text{ppb}/(\text{Mt N}) \end{aligned}$$

These factors come from the combination of the total (dry) mass of the atmosphere, the mean molecular weight of the atmosphere and the molecular weight of the species.

The specifications prescribe the use of radiative forcing expressions from the IPCC Third Assessment Report. The radiative forcing is expressed as a sum over contributions:

$$F(t) = F_{\text{CO}_2}(t) + F_{\text{CH}_4}(t) + F_{\text{N}_2\text{O}}(t) + F_{\text{aerosol}}(t) + \dots \quad (2.4a)$$

(An overlap contribution for CH₄ and N₂O is included in the forcing for these gases).

The individual forcings are expressed as functions of the concentration:

$$F_\eta(t) = f_\eta(C_\eta(t)) \quad (2.4b)$$

For CO₂ we use

$$f_{\text{CO}_2} = 5.35 \ln(C_{\text{CO}_2}/C_{\text{CO}_2:\text{eqm}}) \quad (2.4c)$$

This form is quoted by the IPCC (Ramaswamy et al., 2001: Table 6.2) as one of several alternatives. Other functions are shown in Figure 1, including the older expression previously used by the IPCC in which the factor 6.3 was used instead of 5.35.

$$\begin{aligned} &f_{\text{CH}_4}(C_{\text{CH}_4}) = \\ &0.036 \left[\sqrt{C_{\text{CH}_4}} - \sqrt{C_{\text{CH}_4:\text{eqm}}} \right] - f_{\text{overlap}}(C_{\text{CH}_4}, C_{\text{N}_2\text{O}:\text{eqm}}) + f_{\text{overlap}}(C_{\text{CH}_4:\text{eqm}}, C_{\text{N}_2\text{O}:\text{eqm}}) \quad (2.4d) \end{aligned}$$

$$\begin{aligned} &f_{\text{N}_2\text{O}}(C_{\text{N}_2\text{O}}) = \\ &0.12 \left[\sqrt{C_{\text{N}_2\text{O}}} - \sqrt{C_{\text{N}_2\text{O}:\text{eqm}}} \right] - f_{\text{overlap}}(C_{\text{CH}_4:\text{eqm}}, C_{\text{N}_2\text{O}}) + f_{\text{overlap}}(C_{\text{CH}_4:\text{eqm}}, C_{\text{N}_2\text{O}:\text{eqm}}) \quad (2.4e) \end{aligned}$$

Equation (2.4e) represents a change from the function previously used by the IPCC which had a coefficient of 0.14 rather than 0.12. The CH₄-N₂O overlap contribution is given by:

$$\begin{aligned} &f_{\text{overlap}}(C_{\text{CH}_4}, C_{\text{N}_2\text{O}}) = \\ &0.47 \ln[1 + 2.01 \times 10^{-5} (C_{\text{CH}_4} C_{\text{N}_2\text{O}})^{0.75} + 5.31 \times 10^{-15} C_{\text{CH}_4} (C_{\text{CH}_4} C_{\text{N}_2\text{O}})^{1.72}] \quad (2.4f) \end{aligned}$$

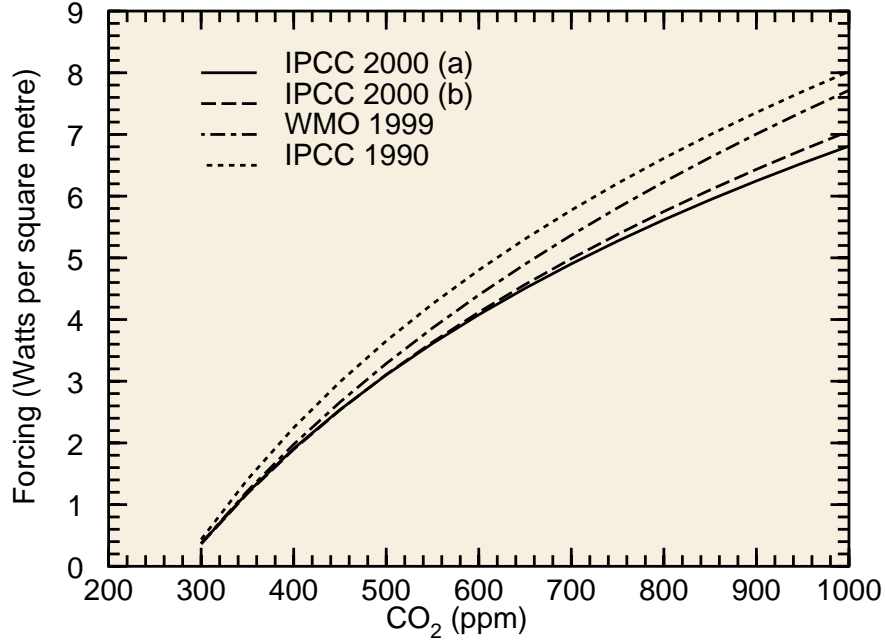


Figure 1: Alternative expressions for the radiative forcing of CO₂ as a function of concentration (Ramaswamy et al., 2001: Table 6.2). Solid curve is equation (2.4c) used in present work. Short dashes are the form from Shine et al. (1990) used in our earlier work.

where in (2.4d,e,f) C_{CH_4} and $C_{\text{N}_2\text{O}}$ are in ppb. We also follow the IPCC (Shine et al., 1990: Table 2.2) and include an indirect effect of methane as a contribution from stratospheric water vapour given by

$$f_{\text{CH}_4:\text{H}_2\text{O}} = 0.011[\sqrt{C_{\text{CH}_4}} - \sqrt{C_{\text{CH}_4:\text{eqm}}}] \quad (2.4g)$$

For other gases, the forcing relation can be treated as linear and expressed in the form:

$$f_{\eta} = a_{\eta}C_{\eta} \quad (2.4h)$$

where the IPCC Third Assessment Report quotes $a_{\text{CFC-11}} = 0.25 \text{ W m}^{-2} (\text{ppb})^{-1}$ and $a_{\text{CFC-12}} = 0.32 \text{ W m}^{-2} (\text{ppb})^{-1}$.

The HadCM3 warming was specified as the response to a delta-function forcing as:

$$W_{\text{default}}(t) = 0.0744423 \exp(-t/8.4007) + 0001038 \exp(-t/409.54) \quad (2.5a)$$

which is used in the form expressing the temperature increase, $T(t)$, in terms of the forcing, $F(t)$, as

$$T(t) = \int_{t_0}^t W(t-t')F(t') dt; \quad (2.5b)$$

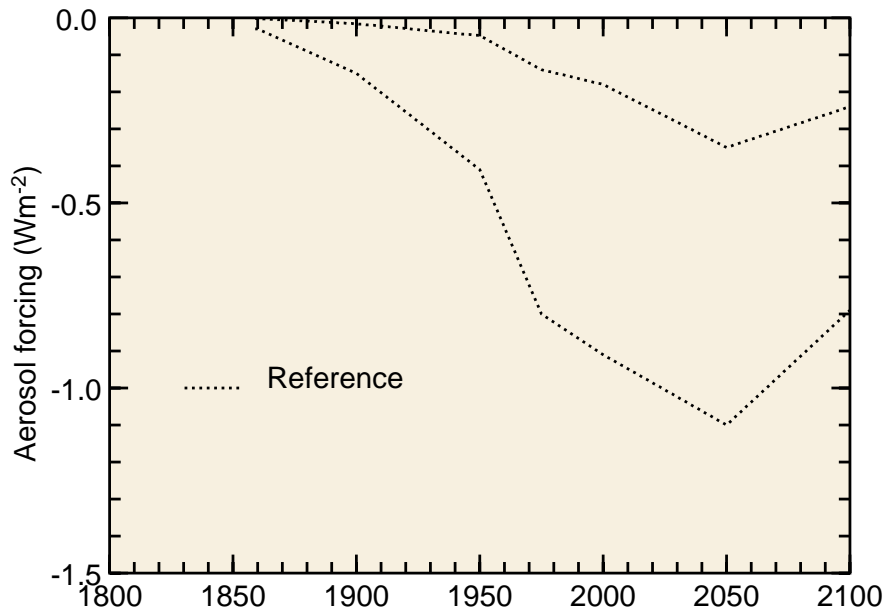


Figure 2: Prescribed aerosol forcing. Future values based on A2 ‘SRES’ scenario. The smaller magnitude component (of each pair once more than 2 are plotted) is direct forcing, the larger magnitude is indirect forcing.

Response function representations of a number of other climate models are listed by den Elzen et al. (1999: Table 3.4).

Similarly, the HadCM3 sea-level rise was specified as the response to a delta-function forcing expressed as:

$$V_{\text{default}}(t) = 6.659 \times 10^{-4} \exp(-t/1700.2) + 3.85 \times 10^{-7} \exp(-t/33.788) \quad (2.6a)$$

which is used in the form giving the sea-level rise, $S(t)$, as

$$S(t) = \int_{t_0}^t V(t-t')F(t') dt; \quad (2.6b)$$

The results of calculations using these default specifications are shown in the various figures as the ‘Default’ curves. Concentrations for the historical period are shown in Figures 3, 5 and 7 for CO₂, CH₄ and N₂O respectively. The corresponding results for 1800–2100 (i.e. with the default SRES A2-marker scenario) are shown in Figures 4, 6 and 8. Figure 9 shows only results from the default case and gives the radiative forcing and its contributions from CO₂, CH₄, N₂O and the two aerosol contributions. Figure 11 gives the warming for 1800–2100.

To summarise, the choices for the ‘default’ for aspects where the specifications were incomplete are:

t	CO ₂	CH ₄	N ₂ O
yr	Pg C y ⁻¹	Tg CH ₄ y ⁻¹	Tg N y ⁻¹
1990.5	7.10	310.0	6.7
2000.5	7.97	323.0	7.0
2010.5	9.58	370.0	8.1
2020.5	12.25	424.0	9.6
2030.5	14.72	486.0	10.7
2040.5	16.07	542.0	11.3
2050.5	17.43	598.0	12.0
2060.5	19.16	654.0	12.9
2070.5	20.89	711.0	13.9
2080.5	23.22	770.0	14.8
2090.5	26.15	829.0	15.7
2100.5	29.09	889.0	16.5

Table 1: SRES A2-marker scenario (Nakićenović et al, 2000: p471).

- In the absence of specified initial conditions we use 280 ppm for CO₂, 700 ppb for CH₄ and 275 ppb for N₂O, based on the IPCC Third Assessment Report.
- In the absence of specified default for historical emissions of CH₄ and N₂O, we have used the EDGAR-HYDE estimates (Aardenne et al., 2001). These have been back-extrapolated (linearly) to zero in 1750.
- We have also used a linear back-extrapolation to zero in 1750 for CO₂ emissions from Land-Use Change.
- We have included an indirect contribution to radiative forcing from stratospheric H₂O produced *in situ* by oxidation of CH₄ (Shine et al., 1990).

3 Validation of CO₂ concentrations

3.1 Background

An important emphasis in this report is on exploring alternative parameterisations of the carbon cycle. This is motivated by:

- results such as Enting et al. (1994) concluding that budget uncertainty is the main contribution uncertainties in projections of future CO₂ concentrations (for a given emissions scenario);

- den Elzen and Schaeffer (2000: Fig. 4d)) finding that carbon budget uncertainty (specifically the role of deforestation) was the main contribution to uncertainty in attribution of relative responsibility for the warming to 1990.

Our modelling framework is being developed to build on our work on uncertainty analysis:

- work on treating the emissions as time series whose values and uncertainties are to be estimated (Trudinger, 2000; Trudinger et al., 2002a,b);
- our approach to capturing model uncertainty through a Bayesian calibration (Enting and Pearman, 1987; Enting and Lassey, 1993; Trudinger, 2000);
- the work by Enting and Trudinger (2001) characterising uncertainties in CO₂ projections in terms of the Laplace Transforms of model responses.

Over the historical period, the primary comparison is with the concentrations observed either directly or recovered from gas trapped in polar ice. However, as can be seen in Figure 3, for CO₂ the reference case follows this curve closely. For the 21st century, the comparison must, of course, simply compare the simple models to the reference case.

The comparisons of the concentrations of CO₂ over the historical period (Figure 3) and for the period to 2100 using the SRES A2-marker scenario (Figure 4) indicate a number of discrepancies. On the whole, these are to be expected on the basis of current understanding:

- i** For CO₂, the 1940's dip is not explicable on the basis of the emissions estimates. This has been further studied by Trudinger (2000) who noted that the ice-core record represents a smoothing of the atmospheric record. The flux variations that caused the dip must have been of larger amplitude than would be implied if the ice-core record was treated as an unsmoothed record of atmospheric concentration.
- ii** the known non-linearities in the response of CO₂ (see Section 3.3 below) mean that response functions linearised about pre-industrial conditions will give a poor representation at high CO₂ concentrations. Therefore the increasing discrepancy over the 21st century is to be expected.

3.2 Budget and calibration

As noted above, current carbon budget uncertainty has been identified as a major contributor to uncertainties in both projections of future CO₂ and attribution of responsibility. Carbon budget uncertainty has generally been addressed in terms of the air/sea partitioning. However, den Elzen and Schaeffer (2001) noted that it was uncertainties in deforestation (i.e. uncertainties in the partitioning between forcing and response) that made the greatest contribution to uncertainty

in attribution. In this context, it is important to consider what Enting (2002: Fig. 14.2) termed the ‘functional role’ of the carbon fluxes.

This issue is illustrated by comparing two alternative views of the so-called ‘missing carbon sink’.

- i The missing sink is an aspect of natural variability (as, for example, explored by Dai and Fung, 1993). Regardless of any systematic trend over recent years, the best estimate for the future behaviour of these processes is taken as zero. This is the assumption underlying a number of the calculations reported in the 1990 IPCC report (e.g. Enting, 1991).
- ii The missing sink is due to processes linked to global change and this linkage will continue into the future. On this basis, the process is often modelled as CO₂-fertilisation, recognising that this may be a proxy for a range of processes such as nitrogen fertilisation. This modelling approach was adopted for the set of model runs reported by Enting et al. (1994) which contributed to the IPCC Radiative Forcing Report and the Second Assessment Report.

For the present study, the ‘functional role’ classification from Enting (2002) can be re-expressed as:

direct anthropogenic forcing These are the emissions that result from human action without a causal dependence on the atmospheric concentration.

response to anthropogenic forcing These are the fluxes that change in response to anthropogenic changes in atmospheric concentration.

natural variation This will be things such as flux variations driven by climate variability as well as ‘internal’ variation due to such things as disturbance and succession in terrestrial ecosystems and circulation/production variations in the oceans. Enting (2002: Section 6.1) noted that the extent to which these variations should be modelled as deterministic vs. stochastic processes will depend on what other information is available.

Wigley and Raper (1992) presented calculations comparing the two budgeting approaches described above. They termed them the ‘no-feedback’ and ‘feedback’ cases respectively and claimed that case (ii) represented balanced carbon budgets while (i) represented unbalanced budgets. Both aspects of this terminology are misleading and inappropriate. As indicated above, the difference lies in how the budget is balanced, not whether it is balanced. Since CO₂-fertilisation represents a direct response to increased atmospheric CO₂ (as does air-sea gas exchange) there seems to be little scientific or semantic justification for describing CO₂-fertilisation as a ‘feedback’, and real potential for confusion with the influence of climate change on the carbon budget.

Wigley and Raper (1992: Fig 1) indicate that the difference in the approach to budgeting will to changes of order 50 to 80 ppm in CO₂ concentrations projected for 2100 with a given scenario.

Note however, that the specific values given by Wigley and Raper incorporate an error that effectively leads to double-counting of the recovery from land-use change (Enting et al., 1994: Technical note A.6.B).

Figure 3 shows a general agreement between the observations and model, apart from the 1940's dip. For more detailed comparisons we can follow the Enting et al. (1994) study and compare the 1980's budget in more detail.

As well as the default response, and our preferred representation (described in Section 3.3) we consider two additional responses:

$$R_{\text{Bern:SAR}}(t) = 0.1369 + 0.1298 \exp(-t/371.6) + 0.1938 \exp(-t/55.70) \\ + 0.2502 \exp(-t/17.01) + 0.2086 \exp(-t/4.16) + 0.0807 \exp(-t/1.33) \quad (3.2.1)$$

specified as an option in the SBSTA intercomparison, and

$$R_{\text{Bern:INIT}}(t) = 0.130164 + 0.333279 \exp(-t/4.144656) \\ + 0.260540 \exp(-t/18.587414) + 0.165742 \exp(-t/58.455562) + 0.110275 \exp(-t/414.962281) \quad (3.2.2)$$

quoted by Enting et al., (1994: Table 9.4).

The comparisons for 1980 to 1990 are:

Case	Response (Eqn.)	C_0 ppm	C(1980.5) ppm	C(1990.5) ppm	growth ppm y^{-1}
Obs.		282.5			1.53
Default	Bern:TAR (2.1)	280	343.5	359.4	1.59
	Bern:SAR (3.2.1)	280	340.6	356.5	1.59
	Bern:INIT (3.2.2)	280	338.3	355.4	1.51
Preferred	Various	280	336.8	352.2	1.54

Ideally, one would like to be able to use this type of comparison as a way of choosing between simple models. There are, however, a number of aspects that limit what can be achieved:

- The problem of using emissions and concentrations to estimate the model response is ill-conditioned. Given a relation $C(t) - C_0 = \int R(t - t')E(t') dt'$, deconvolution for $R(\cdot)$ given $C(\cdot)$ and $E(\cdot)$ is mathematically the same as the 'standard' deconvolution for $E(\cdot)$ given $C(\cdot)$ and $R(\cdot)$ (Enting, 2002: Section 6.6).
- The difficulty in assessing uncertainty can be characterised as one of finding the appropriate set of basis functions to characterise the uncertainty. This has some analogies to the aggregation problem encountered in synthesis inversion (Kaminksi et al., 2001; Enting, 2002: Section 8.3).

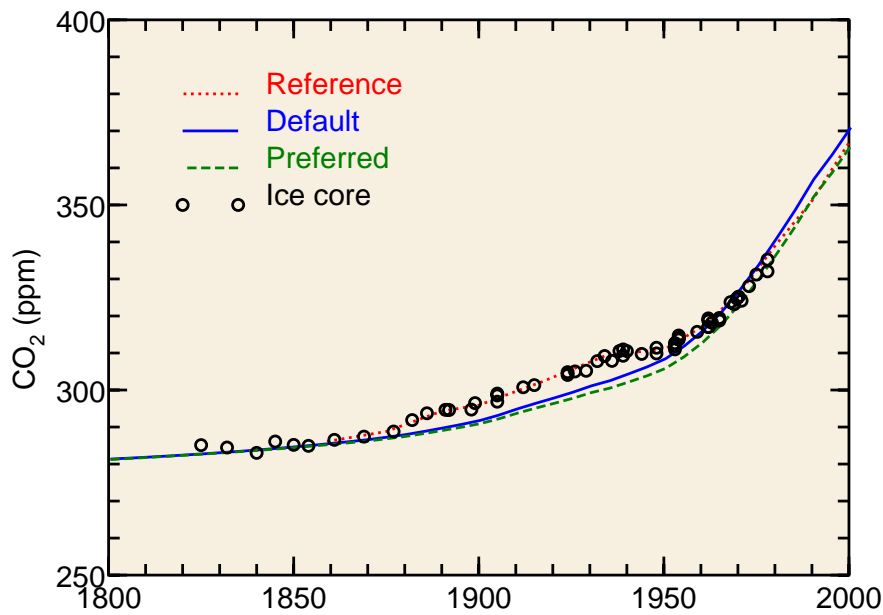


Figure 3: Historical CO₂ concentrations. reference case (dotted line); calculated with default emissions and responses (solid line); calculated with preferred emissions and responses (dashed line);) Law Dome ice core data (Etheridge et al., 1996) (open circles).

- A further difficulty is that emissions are not exactly known. In the worst case, this can lead to circularity (and under-estimation of errors) if models are ‘validated’ with model-derived emission estimates, and at best one is faced with a complex estimation problem.

Some potential solutions to these difficulties can be identified:

- Enting (2002: Box 8.1) quotes Anderssen (1977) as noting that sometimes one does not actually want the solution of such inverse problems, what is required is some linear functional of the solution. In such cases, Anderssen recommends using techniques that calculate the functional directly.
- As a specific example, Enting and Trudinger (2001) characterised uncertainties in projections of future CO₂ in terms of airborne fractions. Using the expression for airborne fraction in terms of the Laplace Transform of the response (e.g. Enting, 1990), they suggested that uncertainties in future projections could be parameterised in terms of how accurately the airborne fraction could be estimated over a calibration period and the sensitivity of the airborne fraction to changes in emission growth rate.
- In analogy to the Enting and Trudinger analysis, we can expect that relative responsibilities for the greenhouse effect will depend on two characteristics: (a) the relative levels of emissions over the attribution period (b) differences in the time distribution within

the period. The contribution to *relative* responsibility from (a) should be insensitive to intermodel differences but differences in relative responsibility associated with different time distributions of emissions can be expected to be sensitive to intermodel differences. (CHECK RIVM STUDY)

A number of proposals have been made for *ad hoc* tuning of response functions:

- The specifications for the SBSTA intercomparison suggest that this should be done via the A_η factors.
- An alternative (T.M.L. Wigley: personal communication — **is this written up somewhere?**) is to modify response functions by (linear) transformation of the time argument.

However, in adopting such tuning, the important point is to ensure that the formalism does not inappropriately reduce the uncertainty. In terms of the discussion above, the tuning should not restrict the range of variation of the linear functionals that reflect attribution, unless such a restriction is inherent in the data used for tuning.

3.3 Non-linearity

An important complication in analysing attribution of the greenhouse effect is the non-linearity in the response of CO₂ from emissions. This non-linearity arises from two main causes:

- non-linearity in the relation between carbon content and CO₂ partial pressure in the ocean surface layer;
- non-linearity (and likely saturation) of the CO₂-fertilisation effect in the terrestrial biota.

The limited validity of linear response function has long been known. Examples explicitly noting different behaviour at higher concentrations are given by Maier-Reimer and Hasselmann (1987) for ocean response functions and Enting et al. (1994) who reported 3 different response functions for the Bern model under conditions of perturbations from (a) pre-industrial (equation 3.2.2); (b) fixed 1990 emissions; (c) the S650 stabilisation scenario.

Because these non-linear effects are most important for future, there are only inter-model comparisons possible. Historical data are little-influenced by the non-linearity. The difficulty is particularly acute for non-linearity in CO₂ fertilisation. In comparison, for air-sea gas exchange the non-linearity is weaker and the behaviour can be predicted from a combination of direct chemical measurements and calculations of chemical equilibrium.

A number of computational techniques have been developed to represent the non-linearity

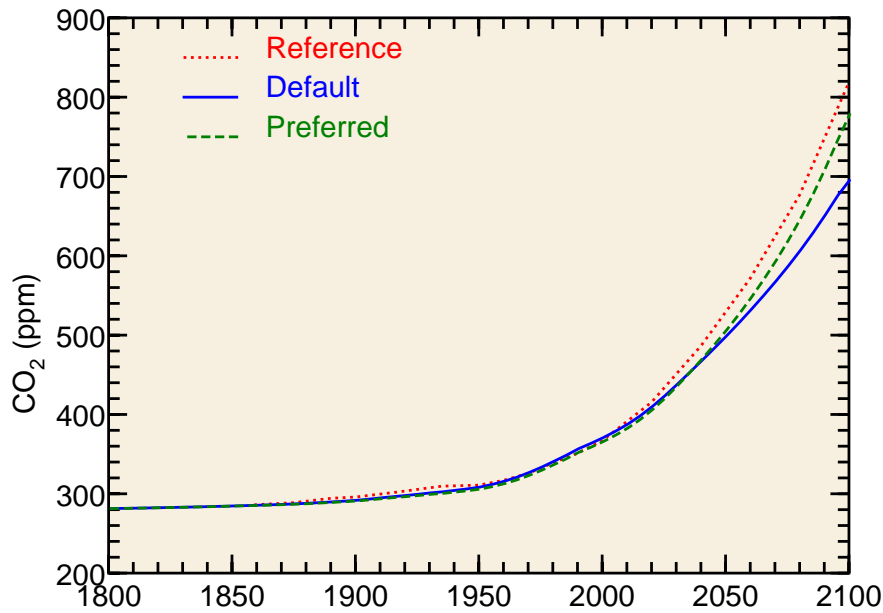


Figure 4: Projected CO₂ concentrations, for SRES A2-marker scenario. reference case (dotted line); calculated with default emissions and response (Solid line); calculated with our preferred representation based on explicit non-linear expressions for air-sea exchange and NPP (dashed line).

- Wigley (1991) interpolated between response functions reported by Maier-Reimer and Hasselmann (1987);
- Joos et al. (1996) proposed explicit modelling of air-sea CO₂ exchange and a response function describing the ocean mixed layer. This approach requires a model of the terrestrial carbon response. This can be excluded explicitly, or included as an enhanced NPP (as an explicit non-linear function) and a decay expressed as a linear response to NPP.

To further quantify the significance of these non-linearities, an additional calculation was performed using the IS92a emission scenario. Using response $R_{\text{Bern:TAR}}$ gave a concentration of 624 ppm in 2100. **re-do with changed $W(t)$** This is lower than results reported by Enting et al. (1994). The models in that study gave ranges, clustered in two groups, around 685 ppm and 725 ppm. This confirms that, as expected from response functions describing perturbations about pre-industrial conditions, $R_{\text{Bern:TAR}}$ gives results that are too small when applied to larger emissions over the 21st century.

Our ‘preferred’ representation of CO₂ is essentially that described by Joos et al (1996). It has an explicit (non-linear) expression for NPP, an explicit (weakly non-linear) expression for air-sea gas exchange, a response function describing mixed layer concentrations responding to air-sea exchange, a response function describing how the respiration and decay in the terrestrial biota responds to changes in NPP. The model expresses the rate of change atmospheric CO₂ content as emissions minus NPP plus respiration minus air-sea exchange. The specific equations are:

For the net-primary-production (NPP):

$$\Phi'_{\text{NPP}} = \Phi_{\text{NPP}}(C) - \Phi_{\text{NPP:eqm}} = \alpha \Phi_{\text{NPP:eqm}} \frac{(G_{\infty} - 1)(C - C_0)}{G_{\infty}(C_0 - C_c) + (C - C_0)} \quad (3.3.1)$$

following Enting and Lassey (1993) in the use of the expression from Allen et al. (1987). Here C_c is the concentration at which photosynthesis ceases, taken as 80 ppm, G_{∞} is the limiting enhancement, taken as 2.4 and the equilibrium NPP is taken as 100 GtCy⁻¹. Notionally, the factor α represents the fraction of the terrestrial NPP to which this enhancement applies. It was used as a tuning parameter by Enting and Lassey.

The air-sea gas exchange is expressed as:

$$\Phi_{\text{AS}} = \kappa [M_{\text{a}} - M_{\text{a:eqm}} - \xi M'_{\text{m}} M_{\text{a:eqm}} / M_{\text{m:eqm}}] \quad (3.3.2a)$$

with

$$y = M'_{\text{m}} / M_{\text{m:eqm}} \quad (3.3.2b)$$

and (from Bacastow, 1981)

$$\xi(y) = 9.36 + 59.56y + 4558y^3 \quad (3.3.2c)$$

The response of the mixed-layer to air-sea flux is expressed as:

$$M'_{\text{m}}(t) = \int R_{\text{mixed}}(t - t') \Phi_{\text{AS}}(t') dt' \quad (3.3.3)$$

and the atmospheric budget is written as

$$\frac{d}{dt} M_{\text{a}} = E(t) - \Phi_{\text{AS}} - \Phi_{\text{NPP}} + \int R_{\text{decay}}(t - t') \Phi_{\text{NPP}}(t') dt' \quad (3.3.4)$$

The Bern model biosphere model has

$$\begin{aligned} R_{\text{decay:Bern}} = & 0.70211 \exp(-0.35t) + 0.013414 \exp(-t/20) \\ & - 0.71848 \exp(-55t/120) + 0.0029323 \exp(-t/100) \end{aligned} \quad (3.3.5a)$$

However, for the present, we use a simple 2-box form of

$$R_{\text{BDM}} = 0.8 \lambda_1 \exp(-\lambda_1 t) + 0.2 \lambda_2 \exp(-\lambda_2 t) \quad (3.3.5b)$$

with $\lambda_1^{-1} = 2$ yr and $\lambda_2^{-1} = 50$ yr. This approximates the behaviour of the two-reservoir biosphere used in our work with the box-diffusion model (e.g. Enting and Lassey, 1993; Trudinger, 2000). With this response function, balanced carbon budgets (balanced according to option (ii) of Section 3.2) correspond to NPP enhancements with $G_{\infty} \approx 2.4$ and $\alpha \approx 1$. Our numerical studies have found that the balance between Φ'_{NPP} and the respiration/decay response are very sensitive to the form of the latter. This needs to be carefully considered in the uncertainty analyses for attribution calculations. Studies of terrestrial response, such as those of Meyer et al. (1999) and Thompson and Randerson (1999), may provide a useful starting point for refining our model.

In describing mixed layer responses, Joos et al. (1996) used distinct representations for short times and times longer than about a year. For the present, we use a single representation based on the long-time form of the HILDA model response from Joos et al. with the amplitude of the fastest decay rescaled to give $R_{\text{mixed}}(0) = 1$. This should be an acceptable approximation for the present studies but it may be unsuitable for isotopic studies.

$$R_{\text{mixed}} \approx 0.022936 + 0.674747 \exp(-t/1.2679) + 0.13963 \exp(-t/5.2528) \\ + 0.089318 \exp(-t/18.601) + 0.037820 \exp(-t/68.736) + 0.035549 \exp(-t/232.3) \quad (3.3.6)$$

This formalism defines our ‘preferred’ case for CO₂, with the parameters tuned to $\alpha\Phi_{\text{NPP:eqm}} = 88 \text{ GtCy}^{-1}$. Figure 3 shows that this representation gives a good fit to the observational data and Figure 4 shows it reproduces the behaviour of the reference case more accurately than would be expected from the spread of models reported by Enting et al. (1994). **IS92a in 2100 is ...**

There are many ways in which one might refine this case. For example, following Trudinger (2000), we could start our integrations from the value 282.5 ppm, reflecting concentrations from before the Little Ice Age. In other words, the Little Ice Age would be treated as an anomaly with little impact on the post-1800 CO₂ record. This is consistent with ¹³C data from ice cores.

4 Validation of concentrations of other greenhouse gases

4.1 Methane

The comparisons of the concentrations of methane over the historical period (Figure 5) and for the period to 2100 using the SRES A2-marker scenario (Figure 6) indicate a number of discrepancies. As with CO₂, these are to be expected on the basis of current understanding:

- i the EDGAR methane budget is consistent with older estimates of order 10 years for the methane lifetime and this is inevitably inconsistent with the newer estimate of 8.4 years.
- ii Over the 21st century, the 8.4 year lifetime leads to increasing discrepancies from the reference case, a longer lifetime being needed. This is expected because of methane's effect on its own lifetime, although quantitative modelling would have to include the effects of other gases (e.g. CO) on the methane lifetime. Analysing the budget of the reference case indicates a lifetime of 10.1 years at the end of the 21st century.

For our 'preferred' representation of CH₄ we use the initial refinement of a time-varying lifetime.

$$\begin{aligned}\lambda^{-1} &= 8.4 && \text{for } t \leq 1900 \\ \lambda^{-1} &= 8.4 + 0.8(t - 1900)/100 && \text{for } t > 1900\end{aligned}$$

Figures 5 and 6 show that this gives results that are significantly closer to the reference case than those given by the default.

The modelled concentrations are higher than the ice-core data. An offset is to be expected because of the spatial gradients in methane concentrations. However, the offset shown in Figure 5 is larger than that implied by spatial gradients.

In defining a 'preferred case' our aim is to have a parameterisation that can be used in a consistent way with the other model components, so that changes in components can be explored independently. However, in exploring the significance of any model component, we would usually expect to go beyond the parameterisations of our preferred case *for that component*. The role of the preferred case in such studies is to specify the behaviour of the other components.

4.2 Nitrous oxide

The comparisons of the concentrations nitrous oxide over the historical period (Figure 7) and for the period to 2100 using the SRES A2-marker scenario (Figure 8) indicate a number of discrepancies. As with CO₂ and CH₄, these are to be expected on the basis of current understanding:

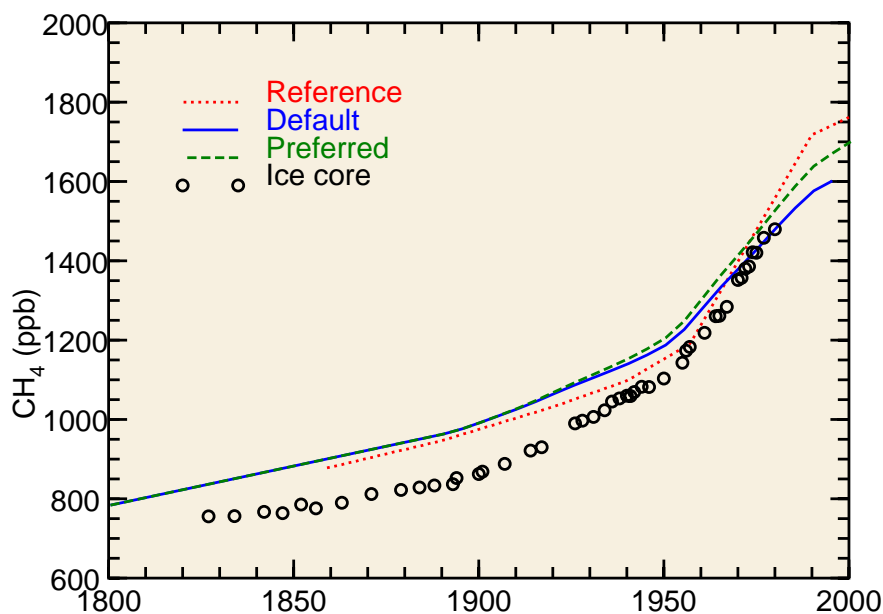


Figure 5: Historical CH_4 concentrations. reference case (dotted curve); calculated with default emissions and response (solid curve); preferred case, using linearly-varying lifetime after 1900 (dashed curve); Law Dome ice core data (Etheridge et al., 1998) (open circles).

- i The EDGAR-HYDE emission estimates are too small to match the observed concentrations. The back-extrapolation to 1750 improves the agreement slightly (since the long lifetime means that the effect of early emissions persists). However the main cause of the discrepancy is that the EDGAR-HYDE estimates for 1990 are 2.85 Tg N y^{-1} while the IPCC Third Assessment Report (Prather et al., 2001) indicates that atmospheric budget analysis implies an anthropogenic N_2O source of 5.7 Tg N y^{-1} .
- ii Comparison with the reference case suggests that the lifetime decreases over the 21st century. This is understood in terms of other changes in the chemical composition of the atmosphere (e.g. Prather et al. 2001, and references therein). However analysing the budget of the reference case indicates a lifetime of about 140 years at the end of the 21st century. Compared to the reference case, the default and preferred cases seem to have lifetimes that are too long early in the 21st century.

For our ‘preferred’ representation of N_2O we use a deconvolution of ice-core data. The emissions over the historical period are calculated as

$$E_{\text{N}_2\text{O}} = \left[\frac{d}{dt} C_{\text{N}_2\text{O}} + C_{\text{N}_2\text{O}}/120.0 \right] / A_{\text{N}_2\text{O}} \quad (4.2.1)$$

Since these emissions are derived directly from observed concentrations, comparisons with concentration data do not provide an validation of the model. In this case, the circularity involved

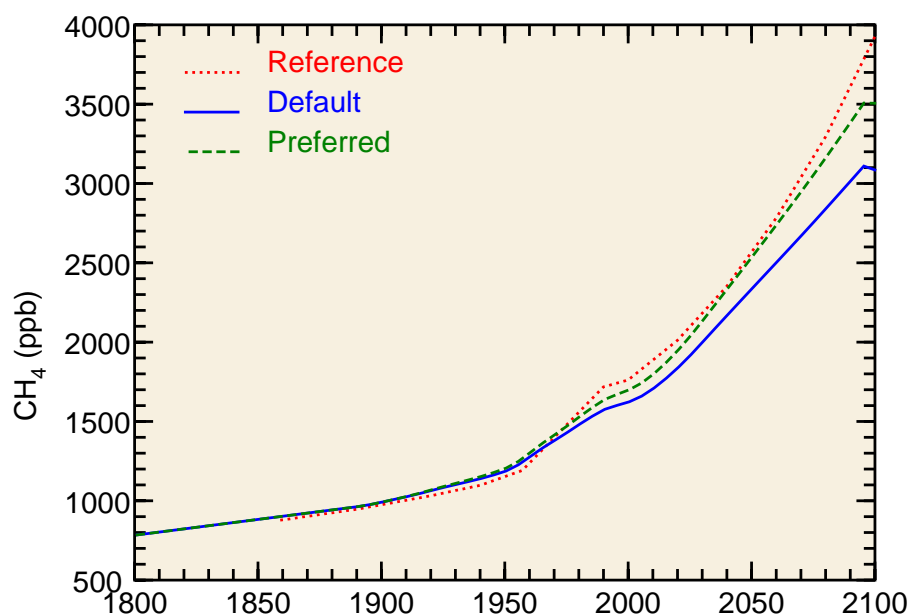


Figure 6: Projected CH₄ concentrations, for SRES A2-marker scenario. reference case (dotted curve); calculated with default emissions and response (solid curve); preferred case, using linearly-varying lifetime after 1900 (dashed curve).

in using concentration data to validate emission estimates is clear. In cases where various forms of tuning have been applied, the circularity can still be present but less obvious.

The incomplete understanding poses a problem for attribution calculations. The ‘preferred’ case here represents a ‘worst case’ making use of no independent source estimates of N₂O over the historical period. While this can, no doubt, be improved, uncertainties in the global budget inevitably imply uncertainties in attribution of components.

4.3 Halocarbons

The halocarbons bring additional complications. The Kyoto Protocol explicitly excludes gases whose emissions are restricted by the Montreal Protocol (including its various amendments). However, since the Brazilian proposal aims to go beyond the Kyoto Protocol, there is no a priori reason for excluding the halocarbons. Currently, the combined radiative forcing from the halocarbons lies between that from methane and that from nitrous oxide. Clearly there is an element of responsibility for the emissions, and compared to other minor gases, the emissions data are of relatively high quality, having been assembled because of the ozone-depleting role of these compounds. Therefore, inclusion of the halocarbons is likely to increase the proportion of forcing and warming that can be reliably attributed.

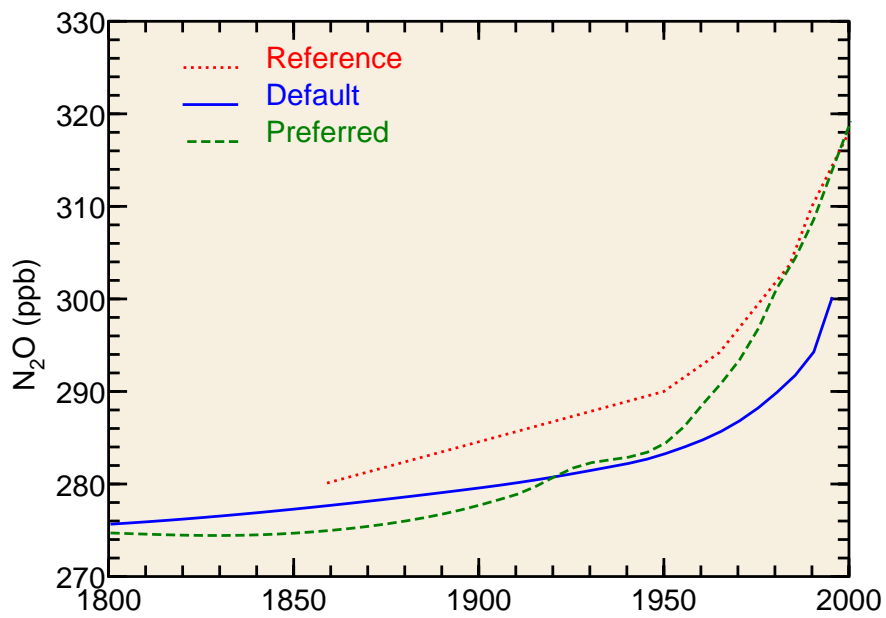


Figure 7: Historical N_2O concentrations. reference case (dotted curve); (b) calculated with default emissions and response (solid curve); preferred case, based on spline fit to ice core data (dashed curve).

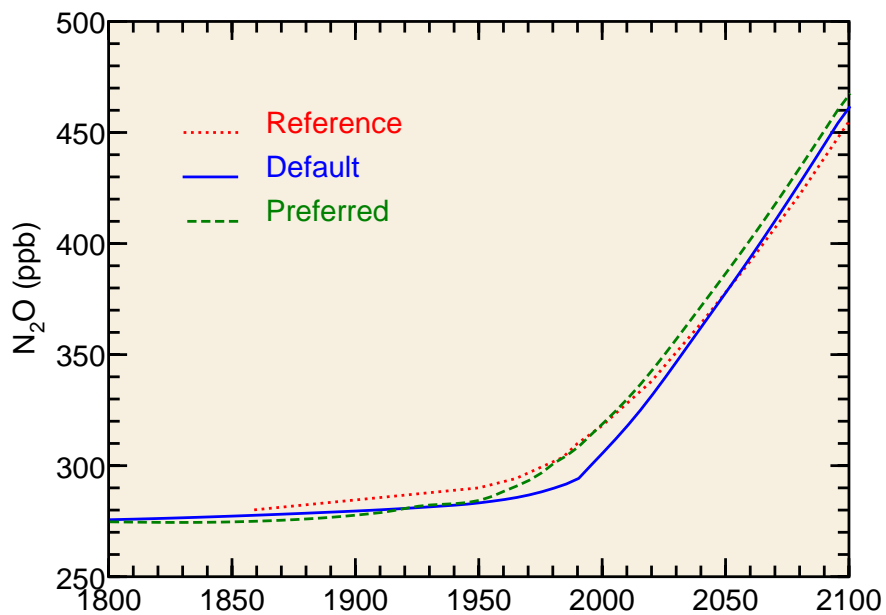


Figure 8: Projected N_2O concentrations, for SRES A2-marker scenario. reference case (dotted curve); calculated with default emissions and response (solid curve); preferred case with emissions during historical period obtained by inversion of ice core data (dashed curve).

One complication that occurs for CFC-12 (CCl_2F_2) (and to a lesser extent other halocarbons) is the time delay between production (and application) and the emission through leakage during use and disposal.

For our preferred case, we use only CFC-11 and CFC-12, and specify concentrations according to the 'Copenhagen-like' scenario given by the IPCC (Prather et al., 1996: Table 2.5d).

5 Validation of forcing and climate

5.1 Forcing

As noted by the SBSTA experts' meeting in Bonn (SBSTA, 2001), validating models against observed temperatures requires that all sources of radiative forcing be included – a rather complex task. Apart from the greenhouse gases, (and gases that indirectly affect the atmospheric budgets of greenhouse gases) the main influences are:

- direct radiative effects of aerosols – this depends on the type of aerosol, with a three-way classification into sulfate, carbon and organic commonly used;
- the indirect effect of aerosols through their role as cloud condensation nuclei;
- changes in stratospheric and tropospheric ozone;
- variations in solar irradiance.

These represent a mixture of anthropogenic and natural influences.

The two difficulties are:

- there is, in many cases, poor knowledge of relation between the radiative forcing and the proximate cause that drives the forcing;
- there is generally poor knowledge of the historical pattern of either the forcing or its driver.

IPCC technical paper no. 2 (Harvey et al., 1997) gives a number of parameterisations of the forcing in terms of drivers. These would provide a starting point for extending the present calculations.

There have been a number of attempts to use empirical fitting to combine estimated histories of forcing. Two such studies are those of Stott et al. (2001) and Forest et al. (2002). Important aspects of the methodology in each case are (a) fitting spatial patterns of response, not just global mean time histories (b) presenting the results in terms of multi-variate distributions of estimates.

5.2 Climate response

As noted in the previous section, uncertainties in the historical forcing severely limit the scope for using calculated vs. observed warming as a basis for choosing between alternative climate

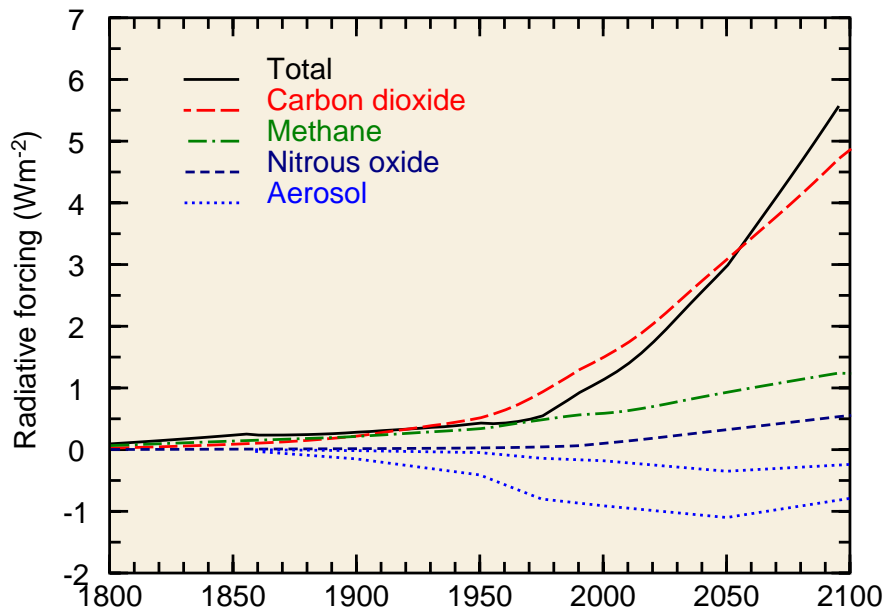


Figure 9: Contributions to radiative forcing for default case.

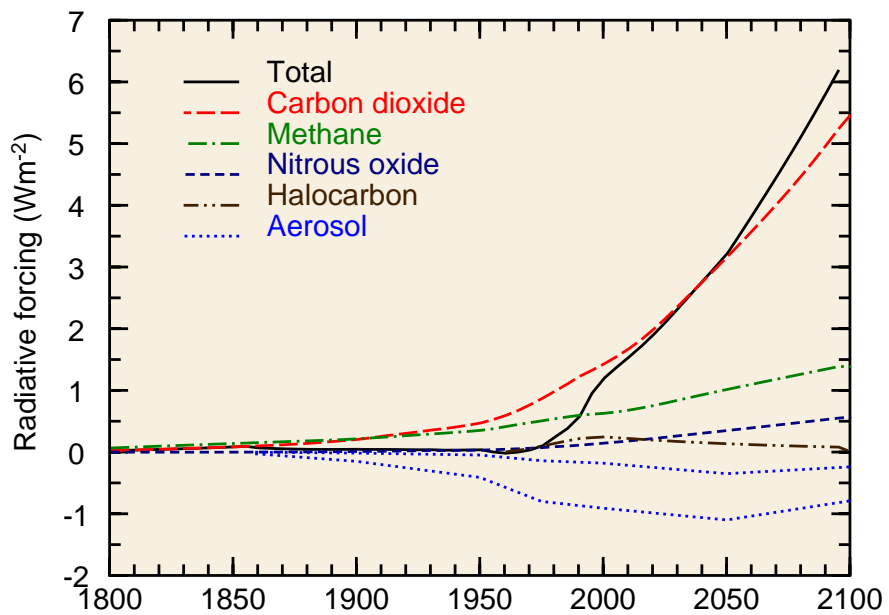


Figure 10: Contributions to radiative forcing for 'preferred' case.

model responses. Any such studies need to be undertaken (as in the references cited above) as joint estimation of climate parameters and forcing parameters.

Beyond such studies, all that we can do is compare a number of different cases, including the default, the response from Hasselmann et al. (1993), the time-dependent response from Watterson (2000) and various cases reported by den Elzen et al. (1999). Two that we note are:

Default This is the HadCM3 response, described by equations (2.5a). Our ‘preferred’ case also uses (2.5a) since the aim is to reproduce the results of the HadCM3 model.

ECHAM-1 This is the single exponential response function given by Hasselmann et al. (1993). We have used this in our previous studies (Enting, 1998; Enting and Law, 2002).

Results for the default are shown in Figure 11. It can be seen that, with the ‘preferred’ representations of greenhouse gases, the temperature curve gives an improved fit to the reference case.

Possible extensions to the analysis of the warming response are:

- Re-parameterise the time-dependent response given by Watterson, so that non-linearity is included explicitly rather than being incorporated through time as a proxy variable.
- Compared to other representations of climate response, equation (2.5a) combines a short time and a very long time, with no multi-decadal component. This is different from many other parameterisations. An explicit consequence is in the emission-time attribution calculations described in Section 6. Compared to the corresponding plots given by Enting and Law (2002) which were calculated with the ECHAM-1 response, the HadCM3 case has no un-realised warming on decadal time scales. This is likely to lead to significant differences in the relative attribution for groups of nations having distinct time histories of emissions, and so further studies of this issue are essential.

6 Emission-time attribution

The ‘default’ cases illustrated in Figures 3, 5 and 7 illustrate the importance of the emissions prior to 1890. While the fit can be improved by back-extrapolation of emissions, this is essentially empirical fitting and provides little basis for partitioning these emissions between national groups. Reliable information at the national level generally begins much later.

The SBSTA intercomparison specifies 3 start dates: 1890, 1950 and 1990. It also specifies calculations with emission end dates of 1990, 2000, 2050 and 2100, with attribution calculations performed for 2000, 2050, 2100 and 2500. We denote the three times involved as t_1 , the start time, t_2 the end time for emissions and t_a , the attribution time. In order to clarify the issues

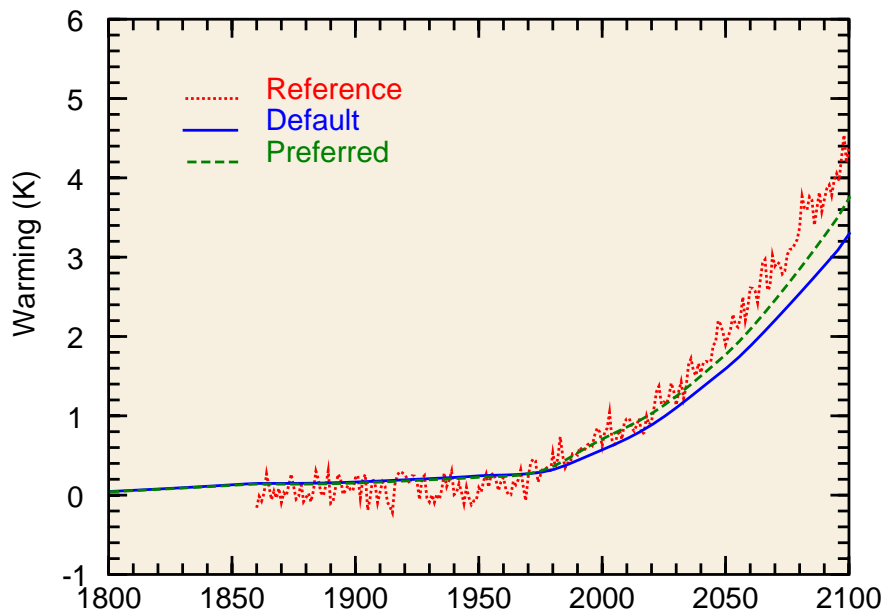


Figure 11: Projected warming, for SRES A2-marker scenario. reference case (dotted curve); (b) calculated with default emissions and response (solid curve); calculated with preferred model (dashed curve).

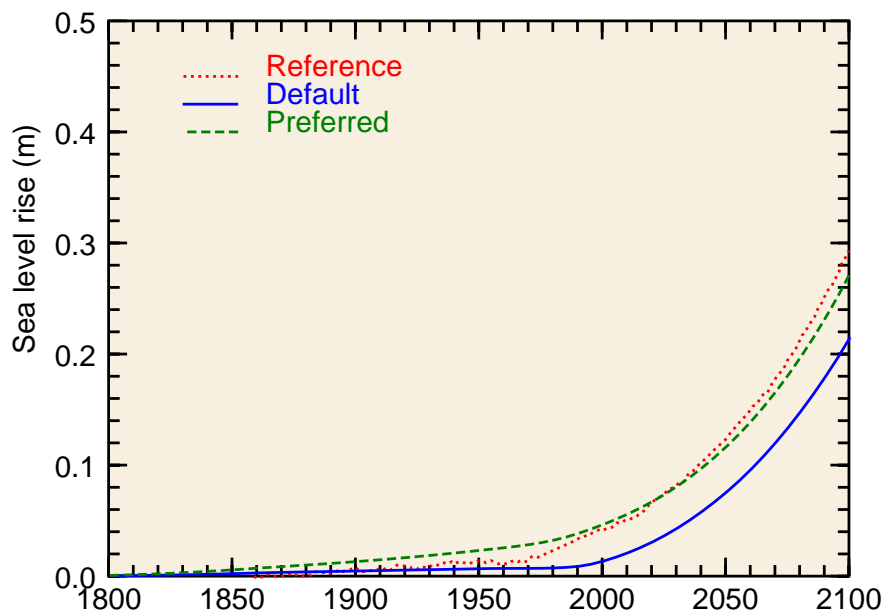


Figure 12: Projected sea-level rise: from reference (dotted curve); with default model (solid curve); with preferred model (dashed curve).

involved, we present (for the default case) the type of ‘time-sliced’ plot discussed by Enting and Law (2002). The various curves annotated with particular years give the amount of warming due to all emissions prior to that year. Following Enting and Law, we use the notation $W(t_a, t_2)$ to denote these curves, where the horizontal axis corresponds to t_a and the curves are for the specific values of t_2 as shown on the plot. To find the warming, at time t_a , due to emissions starting at t_1 and ending at t_2 , we simply take the difference $W(t_a, t_2) - W(t_a, t_1)$, i.e. the difference, on the plot, at time t_a , between the t_2 and t_1 curves.

Enting and Law (2002) noted that for non-linear relations (e.g. the relations between concentrations and forcing) there could be inconsistencies between attribution partitioned by time and attribution partitioned by nations. This would occur with either proportional attribution or with the differential form proposed by Enting (1998). Enting and Law proposed an alternative attribution formalism that, at the cost of some computational effort, was explicitly consistent with emission-time-attribution. Consistency with the emission-time-attribution approach is needed once the attribution is calculated using alternative start dates.

The role of aerosols adds a significant complication to this issue. Figure 13 shows the partitioning of warming according to time of emissions of gases, with the aerosol forcing continuing. It indicates that until a time somewhat after 1990, cessation of gas emissions while continuing aerosol forcing could lead to near-zero warming within a few decades. In contrast, Figure 14 shows cases in which the emissions and the aerosol forcing cease simultaneously. The most immediate consequence is a rapid warming, reflecting the 8-year component of the HadCM2 response (see equation 2.5b).

Hansen et al. (2000) noted the importance of aerosol forcing, and the linkage between CO₂ emissions and aerosols. While this linkage is strong for global aggregates, there are significant differences between nations in the degree of linkage between aerosol emissions and CO₂ emissions.

7 The SBSTA experts’ recommendations

The SBSTA assessment is based largely on recommendations from the Bonn experts’ meeting (SBSTA, 2001). While the present set of calculations merely represent an initial validation stage, it is important to review the recommendations to identify what subsequent steps are needed. The specific recommendations (using the paragraph numbering from SBSTA, 2001) for calculations were (in paraphrased form):

- 26** to use (and compare) a range of different indices for defining responsibility;
- 28** to present results in terms of a variety of socio-economic indicators;
- 32** uncertainties in attribution should be estimated;
- 34** the SRES scenarios should be used to examine sensitivity of attribution to scenario differences;

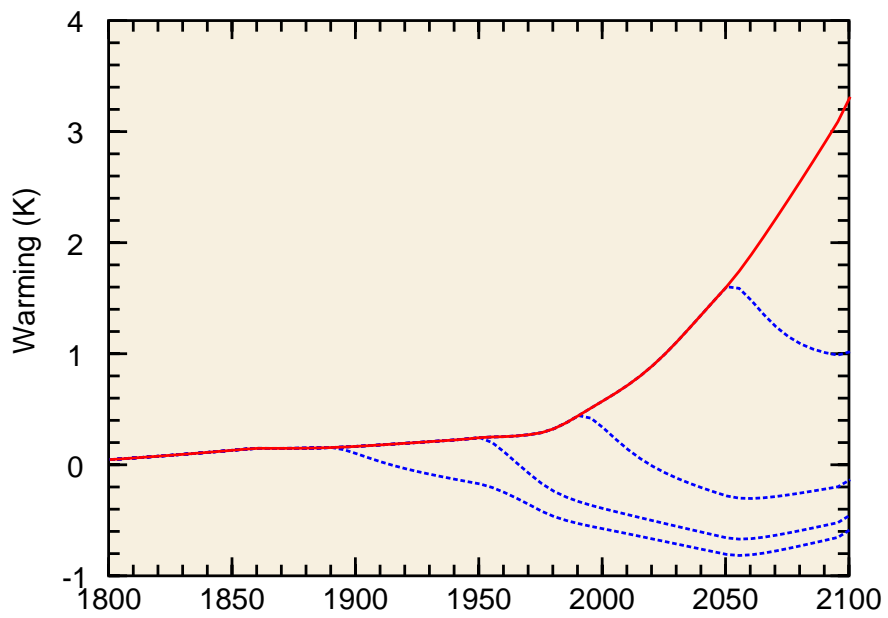


Figure 13: Emission-time-attribution of warming for default case. Solid curve as in Figure 11. Dashed curves are for CO₂, CH₄ and N₂O emissions ceasing at 1890, 1950, 1990 and 2050. Aerosol forcing continues as shown in Figure 2.

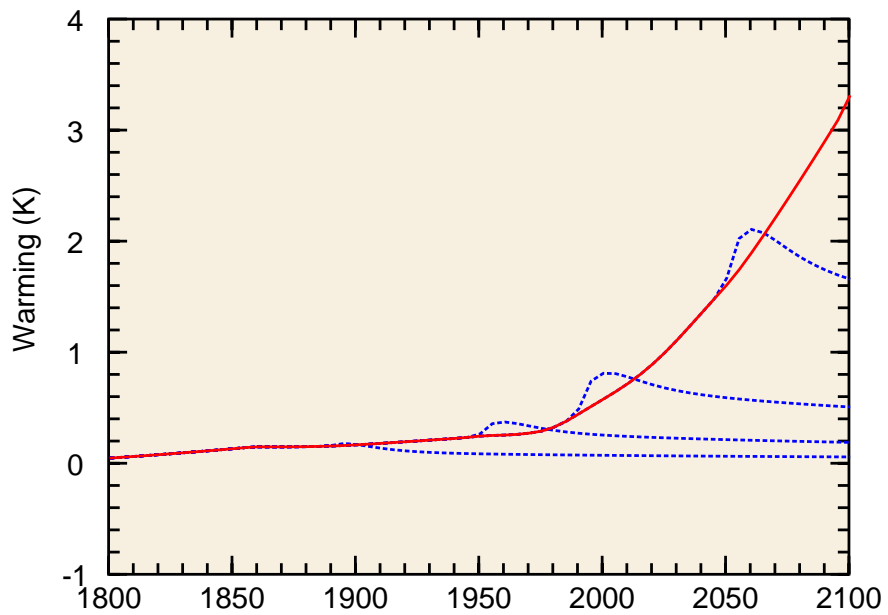


Figure 14: Emission-time-attribution of warming for default case. Solid curve as in Figure 11. Dashed curves are for CO₂, CH₄ and N₂O emissions and aerosol forcing all ceasing at 1890, 1950, 1990 and 2050.

- 36 all greenhouse gases should be included for future periods;
- 37 calculations should assess the sensitivity to uncertainties in historic data, with various choices of start date;
- 38 a range of carbon cycle models should be used;
- 47 the sensitivity to differences in temperature responses should be examined;
- 49 the sensitivity of parameterisations of sea-level rise should be investigated.

The experts also noted a number of other matters that were important for the calculations. These included:

- 41,44 the need to include all contributions to radiative forcing to allow for validation against observed temperatures;
- 45 the need to include non-linearities in the relations between concentrations and forcing;
- 48 the need to include all contributions to sea-level rise.

It was also recommended [30] that the code for participating models should be available.

Given these recommendations, we need to assess our modelling in terms of its ability to address them. Overall, the highly modularised form that we have adopted provides a good basis for performing the requisite sensitivity studies. It has been possible to define a 'preferred' case that is sufficiently close to the reference case from a full GCM, that alternative parameterisations (and the associated uncertainty ranges) can be evaluated in terms of whether the agreement with the reference remains satisfactory.

8 Sensitivity analysis

In studying the sensitivities in attribution calculations it is extremely important to distinguish two different aspects:

- the extent to which the results are sensitive to uncertainties in the science;
- the extent to which the results are sensitive to the choice of methodology.

A number of sensitivities related to each of the classes have been investigated by den Elzen et al. (1999) and more comprehensively by den Elzen and Schaeffer (2000). **CHECK if now published in Climatic Change**

They mainly considered the relative attribution to Annex-1 and others, and identified most important scientific uncertainty as:

- the size of the carbon flux from land-use change and its influence on the carbon budget.

They found that the greatest sensitivity to choice of methodology was (in order of decreasing importance):

- the inclusion of all CO₂ sources vs. only fossil CO₂;
- the inclusion of all gases vs. only CO₂;
- taking account of non-linearities in radiative forcing.

Characterising the uncertainty in parametric models raises the question of the appropriate parameter space to use. In many cases the parameter space required for specifying uncertainties is likely to be larger than the minimal parameter space required to specify the model. Indeed a ‘full’ characterisation of model uncertainty may well require a very large parameter space. However, for the SBSTA exercise, the requirements are, fortunately, much more specific and achievable. What is required is a knowledge of those aspects of model uncertainty that contribute to uncertainty in attribution. As noted in Section 3.2, we are really interested in a functional of the model and therefore only need consider sensitivities and uncertainties within a restricted space.

In exploring ranges of uncertainty from models, the primary constraints come from observations. One needs to determine uncertainty ranges subject to acceptable (but not necessarily exact) agreement with observations in a complex, multi-parameter system. Our previous experience is that a combination of Bayesian calibration, combined with a Lagrange multiplier formalism for exploring extrema of functionals, provides an effective numerical technique for performing such studies (e.g. Enting and Pearman, 1987; Enting and Lassey, 1993).

9 Conclusions

The results presented in this report were calculated using a newly-developed modelling framework based on an object-oriented programming approach. Defining ‘objects’ with, so far as possible, standard interface characteristics, has enabled us to explore a range of different combinations of simple model components. The emphasis has been on addressing the specifications of the SBSTA intercomparison — demonstrating the ability of the simple (parametric) models to reproduce the behaviour of more complex (mechanistic) models. Conversely, in cases where the simple ‘default’ modelling approach appears incapable of reproducing the behaviour of the more complex models, relatively simple refinements have been identified, enabling our models to reproduce the specified behaviour.

The results of the comparisons can be summarised in a few general points:

- i** Matching future concentrations calculated by a more complicated model requires the use of a simple model with non-linear behaviour. Non-linearities in the uptake of CO₂ become increasingly important over the 21st century, as do, to a lesser extent, non-linearities in the response of CH₄ and N₂O.
- ii** If the concentrations over the 21st century are in agreement with those obtained using a more complicated model then the warming matches that of the GCM (if using the default response – from the GCM!!).
- iii** The result that simple models can capture the behaviour of more complex models is hardly surprising. Such models have been used in this way for many years, and their use by the IPCC has been the subject of a special technical paper (Harvey et al., 1997). What remains to be demonstrated is the relation between the parameter space required to reproduce the behaviour and the parameter space required to characterise the uncertainties.
- iv** The emission-time-attribution calculations reveal some of the factors discussed by Enting and Law (2002). Comparing the ‘1890’, ‘1950’ and ‘1990’ curves shows that, over much of the 21st century, the attribution of warming to emissions from the 1890–1950 vs. 1950–1990 periods is, approximately, in the ratio 1:2. This confirms that, information about pre-1950 sources is important, even if warming from such sources is not attributed. In analysing such periods concentration data from ice-cores (and in some cases from the CSIRO air archive) will be important. However, even with such data, the uncertainties regarding current atmospheric budgets of greenhouse gases are likely to be a major contribution to uncertainties in attribution.

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*** Notation**

a_η Radiative effect per unit of gas η in Wm^{-2} per unit mass. For GWPs, $\text{Wm}^{-2}\text{kg}^{-1}$ are used (c.f. Enting and Law, 2002).

A_η Scale factor converting mass units to concentration units for gas η .

C_0 Equilibrium CO_2 concentration in pre-industrial period.

C_c Minimum CO_2 for photosynthesis.

$E(t)$ Emission rate, for CO_2 unless otherwise indicated.

$F(t)$ Radiative forcing.

G_∞ Maximum enhancement factor for NPP.

$F_\eta(t)$ Radiative forcing from constituent η .

M'_m Increase in ocean mixed layer carbon content above pre-industrial equilibrium.

$R(t)$ Response function. For CO_2 unless otherwise indicated.

$R_\eta(t)$ Response function for gas η .

$S(t)$ Sea-level rise.

t Time (in years).

t_0 Initial time, before which net anthropogenic emissions were taken as zero.

t_1 Initial time, when considering anthropogenic emissions over a fixed interval $[t_1, t_2]$.

t_2 Final time, when considering anthropogenic emissions over a fixed interval $[t_1, t_2]$.

t_a Time to which attribution calculations apply.

T Temperature increase.

$W(t)$ Response function for temperature increase driven by radiative forcing.

$W(t, t')$ Warming at time t due to emissions prior to time t' .

$V(t)$ Response function for sea-level rise driven by temperature changes.

Φ_{AS} Air-sea carbon flux.

Φ_{NPP} Net primary production.

Φ'_{NPP} Increase in net primary production relative to equilibrium.

η (as subscript) generic subscript for greenhouse gases.

κ Air-sea gas exchange rate, as inverse of atmospheric turnover time.

τ_η Lifetime for gas η .

ξ Buffer factor.