11. Assessment of Uncertainties

11a. General issues

A very important part of this modelling exercise is the assessment of the uncertainties involved in the CO_2 projections. Some of the key contributions to uncertainties in the model results are:

- Model error;
- Budget uncertainty;
- Imprecise calibration.

There are many aspects of uncertainty analysis and a range of options exists for addressing them:

1. We can investigate the model-dependence by comparing the results of a set of carefully standardised cases. Much of the present exercise adopts this approach.
2. The consequences of the underlying assumptions can also be explored using a set of standardised cases.
3. The sensitivity of the results to variations in model parameters can be explored by systematic exploration of the parameter space (either deterministically or stochastically).
4. A more relevant refinement of (3) is provided by assessing the sensitivity to those sets of parameter variations that lead to results consistent with observations. This can be assessed using a statistical approach to model calibration. Rather than determine fixed sets of parameters seeking exact fits to specific data items, models can be calibrated by determining sets of compatible parameter values that give model results within an acceptable range of observed values.

11b. Relation to the modelling framework

One way of specifying a systematic approach to the analysis of uncertainty is to express it in terms of the general modelling framework described in Section 3b above. The response function form of the carbon cycle may be expressed as

$$N_{\rm a}(t) = 2.123[C(t) - C_0] = \int_0^\infty G_{\rm a}(\tau)\, Q(t-\tau)\, d\tau + \epsilon(t) \qquad (11.1a)$$

or in terms of the Laplace transform:

$$n_{\rm a}(p) = g_{\rm a}(p)\, q(p) \qquad (11.1b)$$

where we have extended the idealised 'error-free' forms used in the discussion above and acknowledged that actual carbon concentrations will include a 'noise' component, $\epsilon(t)$, which is not amenable to modelling.

The equations for rates of change lead to the expression for the airborne fraction defined by (8.1) as

$$r = pn_{\rm a}(p)/q(p) = pg_{\rm a}(p) \tag{11.2}$$

(see Enting, 1990). If $N_{\rm a}(t)$ and $Q(t)$ have exponential growth (with the same time constant) then r is a constant.

The uncertainties in predictions made with the model reflect the uncertainties in the response $G_{\rm a}$, either explicitly as a response function or, more commonly, implicitly in terms of the parameters of a model.

- The first question to arise is how well even a single response can be estimated from the observational data, i.e., how well can $g_{\rm a}(p \approx 0.025)$ (and thus the airborne fraction) be estimated. In the specifications from Appendix A, the suggestion that reasonable fits to the observational data have growth rates for 1990 in the range 1.7 ± 0.1 ppmv y^{-1} addresses this aspect of uncertainty. It implies an uncertainty of ± 6% in the airborne fraction. Such estimates of uncertainty will be applicable to calculations where future emissions grow in a manner comparable to past growth.

- For emission profiles that depart from near-exponential growth, calibrating $g_{\rm a}(p)$ for a single p value is not enough. A more complete specification is required. Given the uncertainties about the current atmospheric carbon budget, a major part of the uncertainty in determining $G_{\rm a}(t)$ will reflect the partitioning of the sink between oceanic and terrestrial components, i.e., in terms of the notation of Section 9c, the relative contributions of $g_{\rm a:oc}$ and $g_{\rm a:bio}$ to the combined response

  $$g_{\rm a} = \frac{g_{\rm a:oc}\, g_{\rm a:bio}}{g_{\rm a:oc} + g_{\rm a:bio} - pg_{\rm a:oc}\, g_{\rm a:bio}} \tag{9.9d}$$

  The specifications in Appendix A do not directly address this aspect of calibration uncertainty. Some assessment can be made by comparing the results from different groups. It is to be expected that this ambiguity will affect calculated values to an increasing extent as emission profiles depart from the past pattern of continuing growth.

- Up to this point, it has been assumed that the calibration has been undertaken with the past anthropogenic source function, $Q(t)$, exactly known. In practice this is not the case. For the 'land-use' component there is considerable uncertainty. Referring back to equation (11.1b), proportional uncertainties in the forcing will have the same effect on estimated responses as the same proportional uncertainty in the response, $n_{\rm a}$. The range 1.6 ± 1.0 implies an uncertainty of ± 15% in the current anthropogenic emissions, and thus in the airborne fraction.

  The instructions in Appendix A provide for the investigation of this aspect of uncertainty by proposing a mean value of 1.6 Gt C y^{-1} for $D_{\rm n}$ over the 1980s with values of 0.6 Gt C

y^{-1} and 2.6 Gt C y^{-1} proposed for exploring the effect of this aspect of budget uncertainty. These are discussed in Section 11d below and they confirm the simple analysis based on Laplace transforms.

- A major contribution to the uncertainty concerns the modelling framework that we have adopted. It is inherent in the assumption that discrepancies in the current atmospheric carbon budget are due to processes that can be explicitly modelled and that such modelling can be extended into the future. More specifically, we have required that the imbalance is to be accounted for in terms of CO_2-induced growth. This assumption corresponds to taking the residual flux $S_{\rm resid}$ in equation (2.1) as being zero. If this assumption is inadequate then the accuracy of future projections will be affected in two ways: firstly through the effects of $S_{\rm resid}$ in the future, and secondly, and more importantly, through the effects of using an incorrect budget in the calibration. The uncertainties arising from this second cause will be equivalent to those arising from the other cases of incorrect budget estimates (i.e., uncertainties in $C(t)$ and $D_{\rm n}(t)$) described above.
- The final aspect of uncertainty is one that is not amenable to systematic analysis: the question of errors in model structure. The comparison between the different model results presented in this report provides examples of a range of different model structures. However, this can not be readily converted into a quantitative assessment of uncertainty. The difficulties are:
    - The relatively small number of models may not adequately sample the range of variability so that the range of variability underestimates the range of uncertainty;
    - The possibility that some key process has been omitted in all models so that the set of results is systematically biased;
    - There is the possibility that some of the highly parameterised models are so crude that they cannot properly represent key processes. In this case, the range of uncertainty based solely on ‘good’ models may be less that the spread of the results presented here.

11c. Previous studies

There have been a number of previous studies that have either compared a range of models or studied uncertainties within the framework of a single model.

Killough and Emanuel (1981) compared five ocean models, each calibrated with ^{14}C. In the terminology of this report, the calculations used inverse initialisations (deducing a terrestrial source/sink history) with forward calculations for the future, and assuming no change in biomass in the future. In spite of the fact that the models had cumulative oceanic uptakes ranging over a factor of 3 for the pre-1975 period, the predictions for future concentrations had a relatively small spread (1800 ± 200 ppmv for 2100 with a logistic release function). These models had airborne fractions significantly greater than those occurring in the present set of calculations.

Laurmann and Spreiter (1983) performed an extensive study of the uncertainties in predictions of future CO_2. Their conclusion was that the proportional uncertainties were small in the cases of growing releases unless the growth rate dropped below 1.5%y^{-1}, and until CO_2 concentrations exceeded 4× pre-industrial levels. They included studies of the effects of (i) linearising the CO_2-fertilisation function (ii) linearising the buffer factor calculations, (iii) changing the exponential growth rate (including the transient effect). They noted larger proportional uncertainties for lower growth rates (including the extreme case of setting future emissions to zero). They noted the potential effect of uncertainties in the deforestation rate on the calibration. However, their quantitative studies of this were confined to analysing the bias introduced by ignoring possible pre-1958 deforestation. Their main conclusion was that for generally increasing releases, the behaviour of the system implied a nearly constant airborne fraction.

Gardner and Trabalka (1985). Perhaps more important than the extent to which the results depend on the model parameters is the question of the sensitivity to those sets of parameter variations that are consistent with the observational data. To address this question, Gardner and Trabalka (1985) used a Monte Carlo approach, generating sets of randomly distributed parameters and looked at the variability of results for the subset of cases that were consistent with observations.

Enting and Pearman (1983, 1986, 1987). Enting and Pearman embedded the sensitivity analysis within the model calibration procedure. This approach has been applied to the case with the box-diffusion model used to calculate the IS92a scenario (Enting and Lassey, 1993). They investigated the question of how much variation was possible in the atmospheric concentration for the year 2100, subject to retaining a specified degree of agreement between the model results and the calibration data.

There have also been several studies that have analysed the uncertainties in projections of CO_2 in terms of the direct sensitivities to model parameters: Kandlikar et al. (1992), Filar (1993), Parkinson et al. (1993), Wigley (1993), Rotmans and den Elzen (1993).

11d. Sensitivity to carbon budget

The instructions in Appendix A prescribe a specific set of calculations to address this question. The budget uncertainty is characterised in terms of uncertainty in the land-use component: the specified calculations require the use of 0.6 and 2.6 Gt C y^{-1} for the 1980s in place of the 1.6 Gt C y^{-1} specified as the standard case. In addition, alternative fits to the CO_2 data were provided giving 1990 growth rates of 1.6 ppmv y^{-1} and 1.8 ppmv y^{-1} in place of the standard 1.7 ppmv y^{-1} (see Figure B.2).

Various sensitivity calculations have been performed using Models J, W and Z.

Land-use Flux, Gt C y^{-1}	0.6	1.6	2.6
β-factor	0.127	0.380	0.626
IS92a*			
$C(2050)$	518	499	486
$C(2100)$	748	688	643
S450			
$E(2100)$	2.28	3.09	3.78
$E(2200)$	1.37	1.64	1.91

Table 11.1. Results from Model J indicating sensitivity to uncertainties in current flux from land-use change.

Table 11.1 shows results from Model J for the IS92a* (i.e., IS92a with the land-use flux going to zero in 2100) forward calculation and the S450 inverse calculation. The 1.6 ± 1.0 Gt C y^{-1} range on the land-use flux corresponds to a ±15% range on the 1980s' anthropogenic forcing. The discussion above would suggest that this would correspond to a ±15% range in the future airborne fraction. The concentration changes, relative to 1990, confirm this expectation. For the S450 calculation, where the emission pattern differs greatly from the continuing growth of the IS92a* scenario, the range of variation in calculated emissions is proportionally larger than the range of variation in current anthropogenic forcing. This example quantifies the qualitative discussion of this aspect in Section 11b.

These calculations enable us to assess the significance of revised estimates of the current carbon budget. The IPCC (1994) report uses a mean 1980s' rate of CO_2 increase of 1.53 ppmv y^{-1} rather than the 1.59 ppmv y^{-1} specified for the model calculations. The revised estimate of the flux from land-use change is 1.1 Gt C y^{-1} rather than 1.6 Gt C y^{-1}, i.e., anthropogenic fluxes of 6.6 Gt C y^{-1} rather than 7.1 Gt C y^{-1}. These changes to the growth rate and the anthropogenic forcing imply changes of -4% and $+7$% in the airborne fraction for the 1980s, relative to that used in the modelling. Thus models calibrated with the IPCC (1994) budget should be expected to have airborne fractions 3% higher than used here and thus give calculated anthropogenic emissions that are about 3% lower than those presented here. The differences can be expected to be somewhat larger for cases stabilising at the lower concentration levels, but in all cases the offset is expected to be much less than the spread of values from the different models.

Click here to go back to contents