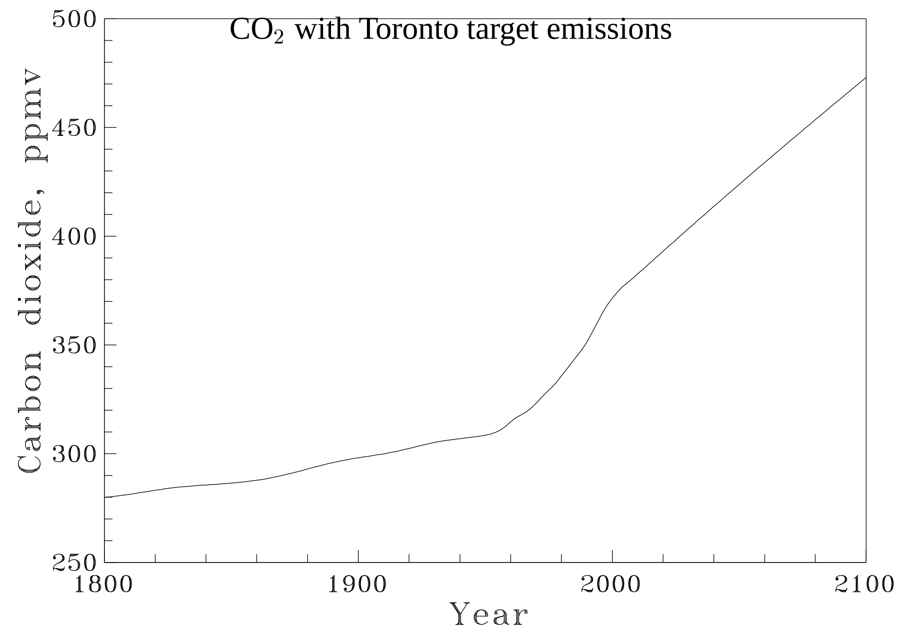
Calculating Future Atmospheric CO_2 Concentrations

I.G. Enting



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Abstract

This report reviews current techniques for calculating the future atmospheric CO_2 concentrations to be expected from various possible patterns of future CO_2 release. Particular attention is given to the calculations presented in the IPCC report (IPCC, 1990) that were obtained using a modified box-diffusion model. Additional results are presented, showing the CO_2 concentrations expected from an adoption of the 'Toronto' target of a 20% reduction in CO_2 emissions by the year 2005. The assumptions underlying these calculations are critically examined.

1. Introduction

Since 1958, precise measurements have shown that the amount of CO_2 in the atmosphere has been increasing. Figure 1 shows the record of CO_2 concentrations from Mauna Loa, Hawaii (Keeling et al., 1989). More recently, it has been possible to analyse the composition of air in bubbles trapped in polar ice. Figure 2 shows some of the data (Friedli et al., 1986; Etheridge et al., 1988; D. Etheridge, personal communication). These data clearly indicate that the increase is associated with the increasing use of fossil fuels. Figure 3 shows estimates of fossil carbon (from fossil fuel use plus cement production) released into the atmosphere each year since 1860. In Figure 4 the same data are plotted on a logarithmic scale, showing that a 4% per annum compound growth rate has typified much of the increase in CO_2 emissions.

Atmospheric CO_2 has the capacity to trap out-going infra-red radiation from the earth. Therefore increases in CO_2 are expected to lead to warming of the earth. This possibility has been recognised since the work of Arrhenius (1896). It has become a serious concern in recent decades with the advent of reliable observations showing that CO_2 is increasing in the atmosphere and computer models of the earth's climate which quantify the amount of warming to be expected.

The CO_2-climate question has been the subject of many conferences and reports throughout the 1980's (e.g. DOE 1985a, b, c, d, e, f, 1987) but the key points of an emerging scientific consensus were the Villach statement, followed by the report of the Intergovernmental Panel on Climatic Change (IPCC, 1990).

In practical terms, the world is faced with the need to both reduce emissions of greenhouse gases and to adapt to climatic change. Without a reduction of emissions, the levels of atmospheric

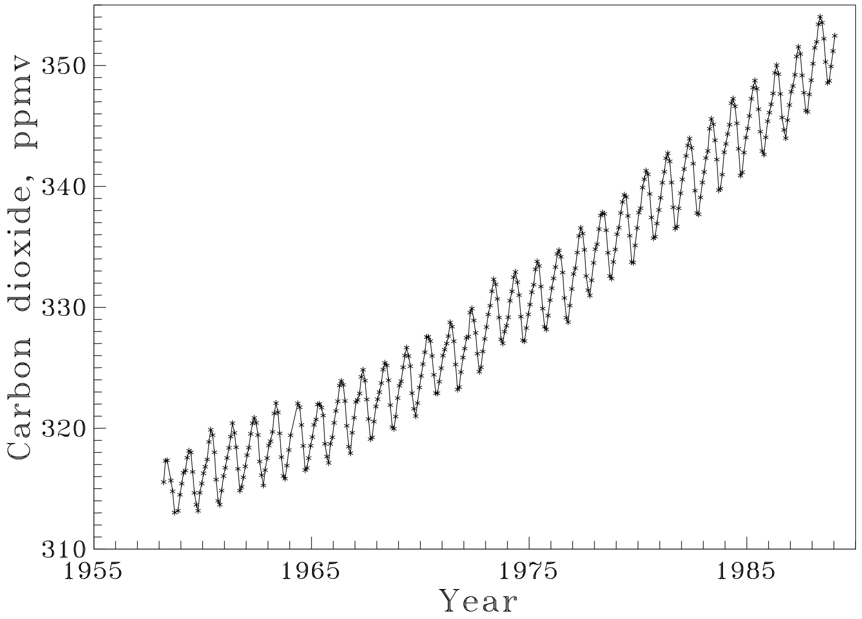

Figure 1: Monthly mean CO_2 concentrations from Mauna Loa, Hawaii; data from Keeling et al. (1989).

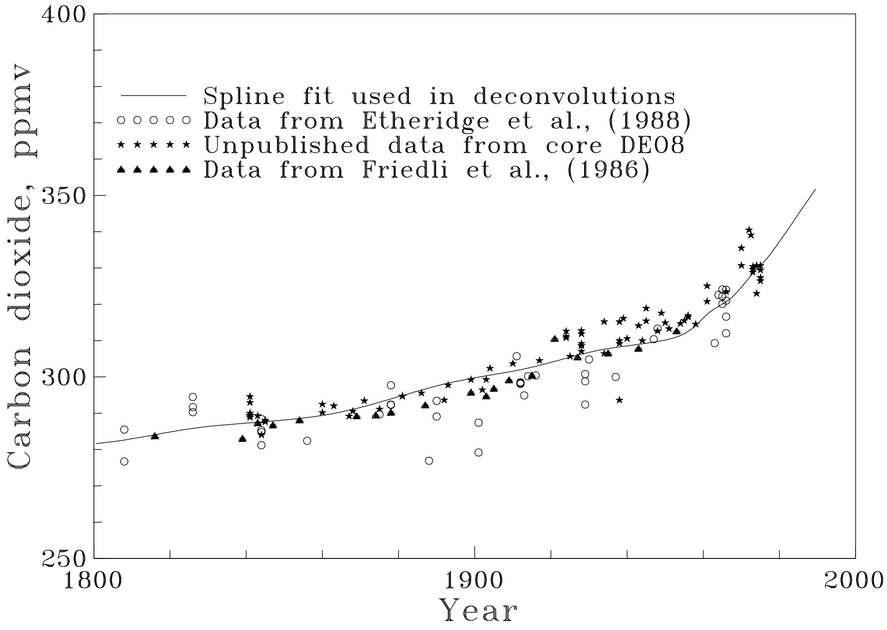

Figure 2: CO_2 concentrations measured in bubbles trapped in polar ice. Data from Frideli et al. (1986), Etheridge et al. (1988), D. Etheridge (personal communication).

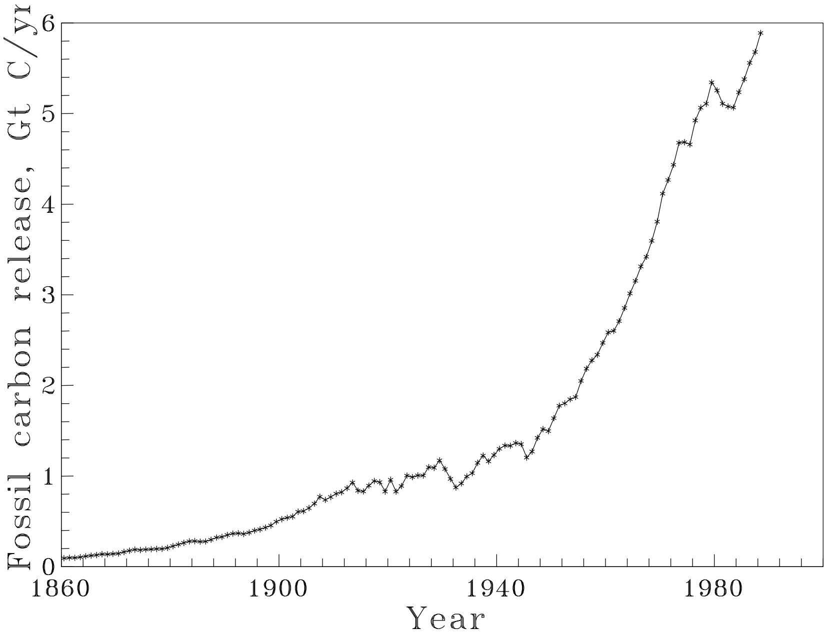

Figure 3: Annual fossil carbon releases, based on data from Keeling (1973), Rotty (1987) and CDIAC (1990).

CO_2, and most probably other greenhouse gases, will continue to increase. The state in which the atmospheric CO_2 concentration is twice the pre-industrial level is often used for discussing climatic effects. However it cannot be emphasised too strongly that a doubled CO_2 level does not represent any sort of natural limit on CO_2 concentrations. CO_2 concentrations will rise much higher than twice the pre-industrial level unless some sort of emission reduction is achieved.

The alternative of reducing emissions, and avoiding climatic change, is probably no longer an option. Hansen (1988) has stated that: *the earth is presently warmer than at any time in the history of instrumental measurements [and] the greenhouse effect is probably the principal cause of the current global warmth.* While most other scientists were less prepared to commit themselves, the temperature record for the years since Hansen's statement can only be regarded as confirmation of the warming. If there has been a detectable greenhouse warming due to CO_2 increasing from 280 ppmv to 350 ppmv, then further warming would be expected even if concentrations were stabilised at 350 ppmv. This is because the oceans are expected to delay the climate warming. In fact, stabilising CO_2 at 350 ppmv is not a practical option. The IPCC calculations indicate that stabilisation at 350 ppmv would require an immediate reduction of emissions to about 30% of the present level followed by a reduction to 20% of present levels over the next decade. These numbers must be treated with caution because the carbon cycle models were designed for calculating changes on decadal time-scales rather than instantaneous changes but regardless of these uncertainties, the reductions are too large to be achievable in practice.

A more reasonable basis for discussing the effects of emission reductions is the IPCC 'science'

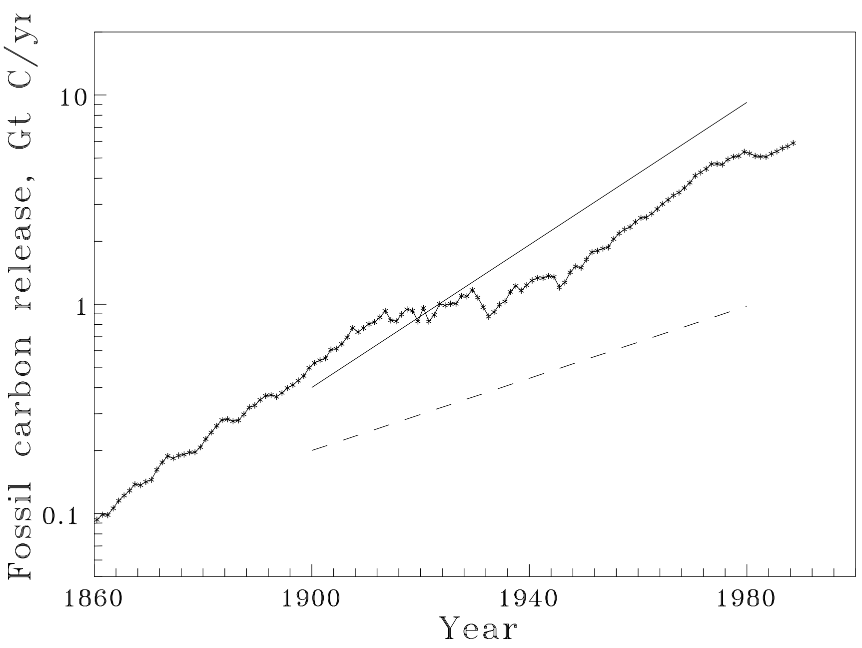

Figure 4: As for Figure 3, but plotted on a logarithmic scale. The solid line shows a slope corresponding to 4% per annum growth, the dashed line a growth rate of 2% per annum.

scenario with a gradual stabilisation at 420 ppmv ($1.5\times$pre-industrial) by the year 2100. The emissions required to achieve this were an immediate freezing of emissions at present levels followed by gradual reductions to 50% of present emissions by 2050 and to about 30% of present levels by 2100. This IPCC 'science' scenario is quite similar to IPCC policy scenario D. The basis of this scenario (IPCC, 1990, appendix 1) is a shift to renewable and nuclear energy, with stringent emission controls in industrialised countries.

Given the magnitude of the changes required to achieve even a modest goal such as stabilising CO_2 at $1.5\times$ pre-industrial levels, it becomes important to reliably calculate the effects of proposed emission reduction strategies. The aims of this report are:

i. to document some of the details and assumptions involved in the IPCC calculations;

ii. to present additional calculations and to describe the techniques for analysing other cases;

iii. to review those areas in which there is scientific uncertainty.

In discussing CO_2 sources and concentrations, two sets of units are most common. Sources and sinks of CO_2 are usually expressed in terms of the mass of carbon involved, rather than the mass of CO_2 which is larger by a factor of $\frac{44}{12}$. The usual mass units are gigatonnes of carbon, abbreviated Gt C, where 1 gigatonne $= 10^9$ (i.e. 1 US billion) tonnes, or 10^{15} gram. Rates of carbon release are expressed as gigatonnes of carbon per year, abbreviated GtCy^{-1}.

Concentrations of CO_2 in the atmosphere are usually expressed in parts per million by volume (as a proportion of dry air), denoted ppmv. Thus 1 ppmv denotes 0.0001% of the volume. A release of CO_2 containing 1 GtC would increase the atmospheric CO_2 concentration by 0.47 ppmv if all the CO_2 remained in the atmosphere.

2. IPCC summary

The IPCC report (IPCC, 1990) covers the atmospheric science aspects of the greenhouse problem. The topics that are addressed in the various chapters of the IPCC report are:

i. Greenhouse gases and aerosols;

ii. Radiative forcing of climate;

iii. Processes and modelling;

iv. Validation of climate models;

v. Equilibrium climate change;

vi. Time–dependent greenhouse-gas-induced climate change;

vii. Observed climate variations and change;

viii. Detection of the greenhouse effect in the observations;

ix. Sea level rise;

x. Effects on ecosystems;

xi. Narrowing the uncertainties.

The present account is concerned with atmospheric CO_2, a topic which is discussed in Chapter 1 of the IPCC report. The report reviews the natural carbon cycle in terms of the atmosphere, oceans and terrestrial biota.

The report presents various calculations of the CO_2 concentrations expected for various possible patterns of future release. For many of these calculations, the simple simulation model discussed in Appendix A was used. The simplicity of the simulation model is not a significant restriction on the accuracy of the calculations. As discussed in section 4c below, and in more technical detail in Appendix B, the behaviour of models with unvarying ocean mixing can be characterised using simple mathematical expressions. Even highly complex models can be represented in this way (see for example, Maier-Reimer and Hasselmann, 1987). The issue for the IPCC calculations is not the simplicity of the simulation model *per se*, but whether it has been correctly tuned to represent the behaviour of atmospheric CO_2.

The conventional way of tuning carbon cycle models is to use the distribution of ^{14}C from nuclear weapons tests. For the IPCC report, the calculations using the box diffusion model departed from this approach by using independent estimates of the model parameters, in order to avoid ambiguities such as those discussed by Enting (1990). However the parameters did not differ greatly from those obtained using ^{14}C and the model gave a reasonably accurate representation of the history of atmospheric ^{14}C in the period after nuclear testing.

The scenario calculations presented in the IPCC report were in two groups: 'policy' scenarios and 'science' scenarios. The 'policy' scenarios were designed to illustrate the consequences of various possible strategies for reducing emissions. The 'science' scenarios were designed to illustrate various aspects of the response of the carbon cycle to changing emission patterns. These various scenario calculations are reviewed in detail in Section 5 below.

The IPCC report, and in particular the executive summary of Chapter 1, noted recent studies that suggested, indirectly, that the oceans and land were currently each taking up about 1 Gt of carbon per year. This is in contrast to the 'conventional' view (based on carbon cycle models calibrated using ^{14}C) which had the oceans taking up about 2 Gt of carbon per year with very little net transfer of carbon to or from the terrestrial biota on an annual average basis. In spite of these indirect studies, the scenario calculations in the IPCC report were based on the conventional view with current oceanic uptake around 2 GtCy^{-1}. These issues are discussed further in subsection 3b below. Another limitation of the IPCC calculations that needs to be noted is that the release scenarios were expressed relative to 1990 fossil carbon releases, and the specified releases were taken as being the sole release after 1990. In only a few of the cases were biomass changes taken into account. In most cases, terrestrial biomass changes after 1990 were taken as zero. This issue is discussed further in subsection 3d below.

3. Sources and sinks

3a. Types of source

From the point of view of the atmosphere, the sources and sinks of carbon are the oceans, the terrestrial biota and fossil carbon. From a modelling point of view it is preferable to consider the atmosphere and ocean as a coupled system with rapid equilibration between the atmosphere and the ocean surface and slow equilibration between the surface and the deep oceans. In this description the external sources are fossil carbon and the terrestrial biota — the air-sea fluxes are treated as internal to the atmosphere-ocean system.

There are a number of approaches used in quantifying the air-sea CO_2 flux.

i Modelling the ocean circulation, along the lines described in Section 4, since the rate of CO_2 uptake is mainly constrained by the rate at which carbon is mixed into the deep oceans. The uptake is a function of the history of CO_2 sources that have established concentration gradients that oppose further uptake.

ii The ‘snapshot’ approach of using the spatial distribution of CO_2 to infer the spatial distribution of the sources and sinks (Enting and Mansbridge, 1989; Tans et al., 1989). Existing data is sufficent to do this only as zonal averages.

iii Ocean chemistry measurements, determining the CO_2 partial pressure (p_{CO2}) in the ocean surface layer. In order to quantify the air-sea flux, Φ, such data are required for all oceans and for all seasons. It is then neccessary to establish the relation between p_{CO2} differences and fluxes, as a function of wind speed. Currently this relation is uncertain to about ± 50%.

The work of Tans et al. (1990) combines [ii] and [iii], using the ‘snapshot’ approach to determine the air-sea flux for the southern hemisphere and ocean chemistry to determine the flux for the tropics and northern hemisphere. The combination gives an estimate of net air-sea flux in the range 0.5 to 1.0 GtCy^{-1}.

The air-sea flux, Φ, is related to Δp the CO_2 partial pressure difference between the atmosphere and ocean by

$$\Phi = \tilde{\kappa}\, \Delta p \tag{1}$$

where the coefficient $\tilde{\kappa}$ is proportional to the atmospheric turnover time κ (see Appendix A). The range 0.5 to 1.0 GtCy^{-1} given by Tans et al. reflects uncertainties in κ.

If one models the response of the atmosphere-ocean system to an increasing CO_2 source, then it is found that the air-sea flux is relatively insensitive to $\tilde{\kappa}$. The main barrier to oceanic uptake of CO_2 is the rate at which excess carbon can be mixed into the deep oceans rather than the transfer into the ocean surface. (This can be shown by consideration of the response functions discussed in Appendix B.)

If, however, one wishes to use the Φ vs Δp relation to determine Φ from measurements of Δp (as was done by Tans et al. 1990), then clearly the flux Φ will be proportional to $\tilde{\kappa}$ and uncertainties in $\tilde{\kappa}$ will produce uncertainties in Φ. Indeed, since the sign of Δp depends on latitude and season, the net air-sea flux Φ involves cancellations of competing contributions and the proportional uncertainty in Φ can be significantly greater than the uncertainty in the average value of $\tilde{\kappa}$. Therefore the analysis by Tans et al. (1990) must be regarded as subject to some doubt and the atmospheric carbon budget as subject to significant uncertainty.

The history of fossil carbon release is reasonably well-known — see Figure 3 above — since most fossil carbon use is associated with economic activity. The sources and sinks from the terrestrial biomass are a much more complex matter. Houghton et al. (1983) have estimated the net biotic carbon release due to land-use changes. Figure 5 shows the estimates for 1860–1980. A number of studies of the global carbon cycle have suggested a significant role for extra biotic growth due to elevated CO_2 concentrations. Such an effect is observed in laboratory studies and sometimes used commercially in real greenhouses. Extrapolating from short term laboratory studies to a global space scale and decadal time scales is extremely uncertain. Kohlmaier et al. (1987) have modelled the CO_2-fertilisation effect on a global scale but acknowledge that the parameterisations are highly uncertain. In addition, the question of the role of the terrestrial

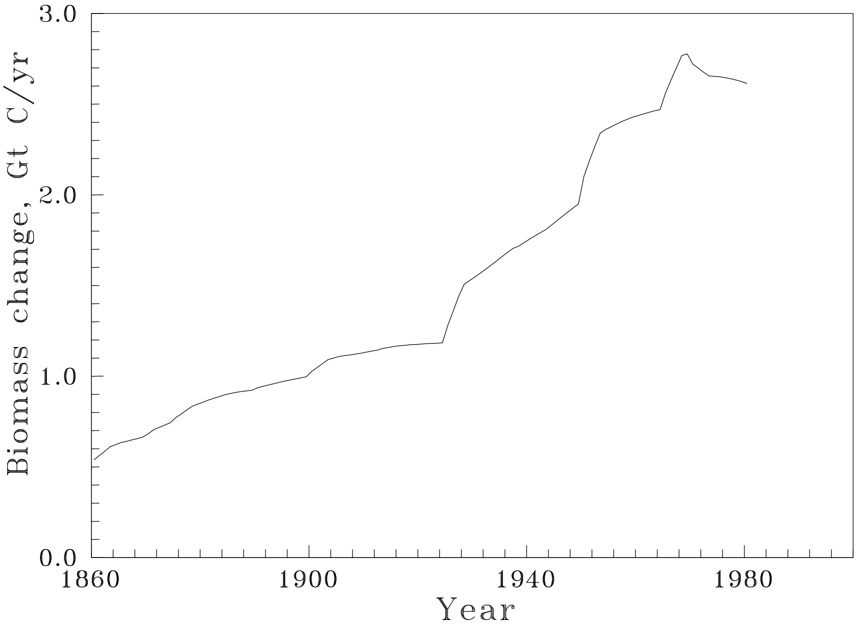

Figure 5: Estimates of annual CO_2 releases due to land-use changes as calculated by Houghton et al. (1983).

carbon budget is complicated by other processes such as changed fire regimes, eutrophication, toxification from industrial pollutants and other forms of forest degradation.

3b. Uncertainties

The IPCC calculations are based on what could be called the ‘conventional’ view of the atmospheric budget. For the early 1980’s, this comprised:

3 $GtCy^{-1}$ increase in atmospheric carbon, determined by direct observations

just over 5 $GtCy^{-1}$ input of fossil carbon

approximately 2 $GtCy^{-1}$ taken up by the oceans, as determined by models calibrated using ^{14}C.

a small net contribution from the terrestrial biota.

This conventional view has been called into question in two main ways:

i. The release estimates from Houghton et al. (1983) (see Figure 5 above) suggest a 2 $GtCy^{-1}$ release from the biota rather than the small exchange obtained from conventional atmospheric carbon budgets.

ii. Studies using the spatial distribution of CO_2 to infer the spatial distribution of sources found that the ratio of northern hemisphere to southern hemisphere sinks was much greater than would be expected for ocean sinks on the basis of area. The study by Tans et al. (1990) combined such estimates with ocean CO_2 partial pressure data to produce an estimate of oceanic uptake in the range 0.5 to 1.0 GtCy^{-1}. The atmospheric carbon budget would thus require a *net* biotic sink of 1 to 1.5 GtCy^{-1}, and if deforestation is releasing 2 GtCy^{-1}, then a biotic sink of 3 GtCy^{-1} or more is required.

A number of approaches are being used in an attempt to reduce these uncertainties:

i. attempts to refine direct estimates of terrestrial biomass changes;

ii. attempts to refine ocean models for calculating CO_2 uptake;

iii. observations of ocean chemistry and studies of air-sea gas exchange, designed to give a direct estimate of the net uptake of CO_2 by the oceans;

iv. use of carbon isotope data to provide additional constraints on the carbon cycle;

v. refining the ‘snapshot’ approach that uses the spatial distribution of atmospheric CO_2 to infer the spatial distribution of sources and sinks, thereby constraining the possible types of sources and sinks.

vi. Enting and Mansbridge (1991) have suggested that some of the discrepancy between the Tans et al. analysis and global carbon cycle modelling lies in the incomplete treatment by Tans et al. of the role of CO in the atmospheric carbon cycle.

vii. recently it has become possible to measure the amount of oxygen in the atmosphere (as an O_2:N_2 ratio) with sufficient precision to constrain the atmospheric carbon budget (Keeling, 1988).

Each of the areas listed above can involve many different types of study.

In addition to the approaches listed above, a number of other studies give relevant peripheral information. One intriguing piece of information concerns the amplitude of the annual cycle of atmospheric CO_2. This has shown an overall increase over the course of the record since 1958. More precisely, the amplitude was relatively constant until about 1975 and then grew over the period 1977–1980 and has since been relatively constant (or even possibly declining slightly). The increase in the cycle may represent an increase in terrestrial biomass but it could equally well represent greater biotic activity in a fixed biomass, resulting for example, from increased temperatures.

The interannual variations in the Mauna Loa cycle were studied by Enting (1987) — a refined analysis is given by Enting and Manning (1989). This work found a characteristic correlation in the amplitudes for the period 1958–1975 suggesting that the interannual variations arose from abnormal growing seasons whose effects were dissipated over several following years and not just the following winter. Subsequent work by Thoning et al. (unpublished result, presented at Hinterzarten CO_2 conference, 1989) found that this correlation structure did not persist after 1980. Whether this change in correlation structure has a common cause with the increase in amplitude or whether the results for correlations were a statistical fluke, remains unclear.

3c. Deconvolution

One way of estimating the history of biotic contributions to the atmospheric CO_2 budget is to use the concentration history to deduce the source history. Measurements of gas concentrations in bubbles trapped in polar ice provide a record of atmospheric CO_2 concentrations over the industrial period (eg. Neftel et al., 1985). If the model is forced to follow this concentration history, the air-sea flux can be deduced from the model equations, and the terrestrial source is whatever additional input is needed in order to match the measured growth in atmospheric CO_2. The biotic source can be obtained by subtracting the fossil fuel source from the terrestrial source determined in this way. A series of calculations of this type was presented by Siegenthaler and Oeschger (1987).

In mathematical terms this is a deconvolution, i.e. an inversion of equation (3) of Section 4c below, to determine the source, $S(t)$, from the concentrations, $C(t)$. In such problems, the results can be very sensitive to errors in the inputs and in the models used in the inversion (see Enting and Newsam, 1990, for further discussion). In the numerical model the sensitivity arises largely from the need to numerically differentiate the observational data specify the rate of CO_2 increase, $\frac{dC}{dt}$, since the sources are determined by matching the measured growth rate.

This approach of deducing the biotic source history from the ice-core data was used for the IPCC calculations based on the box-diffusion model. The CO_2 record was represented by a smoothing spline fitted to the combination of ice-core data from Neftel et al. (1985) and direct observations from Mauna Loa. The combinations of data weighting and smoothing parameter were adjusted so that the smoothing spline gave 50% attenuation of signals with period 50 years in the ice-core record and 50% attenuation of signals of period 7 years in the Mauna Loa record. The curve is shown in Figure 6.

3d. Extrapolating biotic releases

The advantage of the deconvolution approach described above is that it reproduces the observed history of CO_2 variations. The disadvantage is that it does so by curve-fitting rather than modelling the biotic processes and so it gives no basis for representing biotic changes in the future.

The procedure adopted in the IPCC calculations using the box-diffusion model was to use the deconvolution method prior to 1990 and then to arbitrarily set the net biotic carbon flux to zero there-after. Some obvious comments on this procedure are:

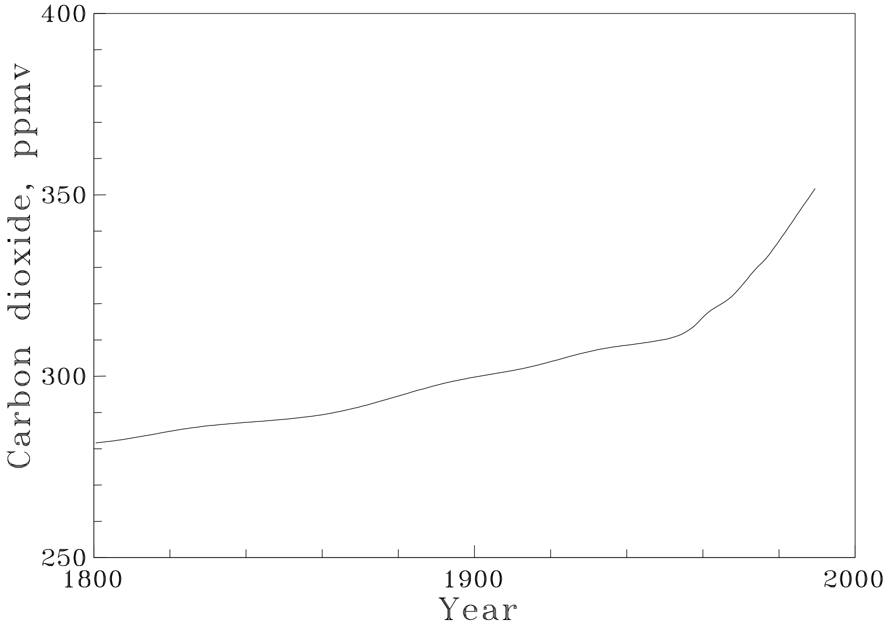

Figure 6: The representation of atmospheric CO_2 for 1800 to 1990 as used in the IPCC calculations. The curve is a spline fit to a combination of ice-core data and direct observations.

For predicting the future, it may be a reasonable assumption under the ‘conventional’ view in which the net change in terrestrial biomass is currently small.

In any case it provides a fixed reference assumption, with respect to which the relative effectiveness of various fossil-fuel reduction strategies can be compared. To the extent that the atmosphere-ocean system responds linearly to inputs, all scenario calculations will be subject to the same bias due to neglect of future biotic changes.

The errors will be most important when analysing the greatest reductions. In particular they will be important for the calculations analysing stabilisation of atmospheric CO_2 at 1990 levels. (Or equally important for analysing instantaneous stabilisation at some future point — 1990 has passed without any such change!) As discussed in Section 5 below, the calculations for instantaneous stabilisation involve time-scales shorter that those for which the models were designed. The inadequate treatment of the biota is simply one more reason why these ‘stabilisation’ calculations should be regarded as more of symbolic than of practical interest.

In principle one could improve the modelling by having the model represent both the anthropogenic changes and the natural biotic response. At the simplest level, this could be done by combining the estimated releases from land-use changes (Houghton et al., 1983: see Figure 5 above) and some model of CO_2-induced growth. It would be neccessary to tune this combined model so as to adequately reproduce the past CO_2 concentrations. A recent study by Enting

(1992) indicates that it may not be possible to fit past concentrations with this type of model unless additional processes are invoked.

If such a model could be obtained then it could be used with a combined scenario of fossil carbon releases and anthropogenic influences on the terrestrial biota. A response function represention of such a model is described in appendix C.

4. Modelling approaches

4a. Simulation models

In the previous section, it was noted that the main barrier to oceanic uptake of CO_2 is the mixing into the deep ocean. There are two main types of model used to simulate this mixing. The first class are simple highly parameterised models whose mixing is calibrated by considering other tracers. In CO_2 studies, ^{14}C from nuclear tests has often been used in this way. The other approach is to calculate the ocean mixing from the basic dynamical equations using an ocean general circulation model (GCM).

There is a wide gap between these classes of models, in contrast to the situation in atmospheric transport modelling where one has simple one-dimensional models and at the other extreme three-dimensional GCM-based transport models. However atmospheric GCMs are less demanding in their computing requirements than ocean GCMs. More importantly two-dimensional zonally-averaged atmospheric transport models constitute an important, widely used, intermediate class for which there is no oceanic analogue.

Ocean GCM modelling has been used in carbon cycle studies by Sarmiento (1986) and Maier-Reimer and Hasselmann (1987).

Of the simple parameterised ocean models, the most widely used in CO_2 studies is the box-diffusion model of Oeschger et al. (1975). A critical limitation of such models is the calibration problems — for example the question of the extent to which the model structure distorts the relation between different tracers so as to bias the calibration. In an attempt to extend the scope of these parameterised models, Bolin et al. (1983) considered a 12-reservoir ocean model and used data for C, ^{14}C, O, P and alkalinity to calibrate it. This approach could not produce a consistent calibration — the reasons for this remain unclear.

4b. Airborne fraction and atmospheric lifetime

Predicting future CO_2 concentrations is a matter of relating concentrations to sources. To do this in the most general case requires a full model simulation of the processes involved along the lines described above. For relatively staightforward systems, the response function formalism described in the following subsection can parameterise the behaviour of numerical models so the concentrations can be calculated using the response function rather than the full model. In even more restricted cases, it becomes possible to characterise the relation between sources and concentrations in terms of a single number. The two most commonly used quantities of this type are the airborne fraction, ρ and the atmospheric lifetime, τ.

The airborne fraction can be defined in a number of ways. One of the most popular is

$$\rho = \frac{dC}{dt} \Big/ S(t) \tag{2}$$

where the atmospheric CO_2 content, $C(t)$, is expressed in terms of mass units consistent with the source, $S(t)$. If the Mauna Loa record is analysed, assuming that the only source is the fossil carbon release shown in Figure 3, then the airborne fraction is found to be about 0.55.

In a linear stationary system (see subsection 4c below for definitions), exponentially increasing sources lead to exponentially increasing concentrations and the airborne fraction is constant in time but dependent on the rate of exponential growth. In other situations, ρ is not usually constant although assuming a constant ρ can be a reasonable approximation so long as the sources are steadily increasing.

However, the assumption of a constant airborne fraction is misleading when discussing possible emission reductions. Stabilisation of atmospheric concentration corresponds to $\frac{dC}{dt} = 0$. This can be achieved without having $S(t) = 0$. Similarly, for sufficiently large reductions, $\frac{dC}{dt}$ can become negative while $S(t)$ remains positive, albeit small.

The atmospheric lifetime, τ, is best applied to compounds such as CH_4 where τ is a measure of a destruction rate that is proportional to concentration. In this case τ is the time for a perturbation to decay to 37% (i.e. a factor of $\frac{1}{e}$) of its original size.

For CO_2, perturbing inputs into the atmosphere are dissipated by mixing into the ocean, rather than chemical destruction. The accumulation of carbon in the ocean tends to retard further uptake so a perturbation will decay more slowly than the exponential decay characterised by a single atmospheric lifetime. In fact the process of mixing of CO_2 into the ocean establishes an equilibrium in which an atmospheric perturbation is never fully dissipated.

Nevertheless, various phases of the oceanic uptake of CO_2 can be described approximately in terms of an effective atmospheric lifetime.

The IPCC report makes some use of this approach when making qualitative comparisons between CO_2 and other greenhouse gases for which the atmospheric lifetime is well-defined. For numerical calculations, such as those of warming potentials of CO_2 the IPCC calculations take into account the more complex behavior that is characterised by the response functions defined in the following subsection.

4c. Response functions

The response function formalism relies on two characteristics that are assumed to apply to the atmosphere/ocean system: stationarity and linearity. Stationarity requires that the response to an input of CO_2 into the atmosphere does not depend on the time at which the input occurs. The resulting excess concentration must decay in the same way regardless of whether the release was in 1880 or 1980. This requires the ocean mixing processes to have been constant. The linearity property requires that twice the input will lead to twice the excess CO_2 both at the time of input and as the perturbation decays. More generally the atmospheric concentration must be able to be expressed as a sum of perturbations from all the individual input contributions.

Under these assumptions we can define a response function, $R(t)$, which gives the amount of CO_2 in the atmosphere at a time t after a unit input. It follows that

$$C(t) = C(t_0) + \int_{t_0}^{t} R(t-t')\, S(t')\, dt' \tag{3}$$

where t_0 is the beginning of the industrial period at which time an equilibrium pre-industrial CO_2 concentration, $C(t_0)$ is assumed. The units of $R(t)$ depend on the units of $C(t)$ and $S(t)$. For CO_2 we will generally express sources in GtCy^{-1} (10^9 tonnes of carbon per year). If the atmospheric CO_2 content is expressed in Gt C, then $R(t)$ is dimensionless and $R(0) = 1$. If $C(t)$ is expressed in the concentration units, the $R(t)$ is in ppmv per Gt C, and $R(0) = 0.471$ ppmv per Gt C.

Describing a model in terms of its response function is a valuable way of communicating the behaviour of the model. Other workers can explore the characteristics of the model without having to have a full computer model implemented. This counters the criticism of Hammond et al. (1990) that sophisticated models of the carbon cycle are inaccessable and therefore unsuitable for use by policymakers as opposed to scientists.

For many greenhouse gases, the response function can be closely represented by a single exponential, $A_x \exp(-t/\tau_x)$ in which case τ_x is the atmospheric lifetime for constituent x. For CO_2, the response function is not well-represented by any single exponential although such an approximation may be adequate for special purposes. The best choice of exponential will depend on the application — this is what is meant when the IPCC report notes that the specification of a single lifetime for CO_2 presents difficulties.

For CO_2 a better approach is to represent the response as a sum of exponentials. This is discussed in detail in appendix B below. An example of such a representation is the approximation

$$\frac{R(t)}{R(0)} = 0.131 + 0.201e^{-t/362.9} + 0.321e^{-t/73.6} + 0.249e^{-t/17.3} + 0.098e^{-t/1.9} \tag{4}$$

quoted by Maier-Reimer and Hasselmann (1987) as representing the response of their ocean GCM to CO_2 perturbations. They found that the linearity property, on which the response function formalism is based, was a good approximation for perturbations up to a doubling of CO_2, but broke down when considering quadrupling of CO_2.

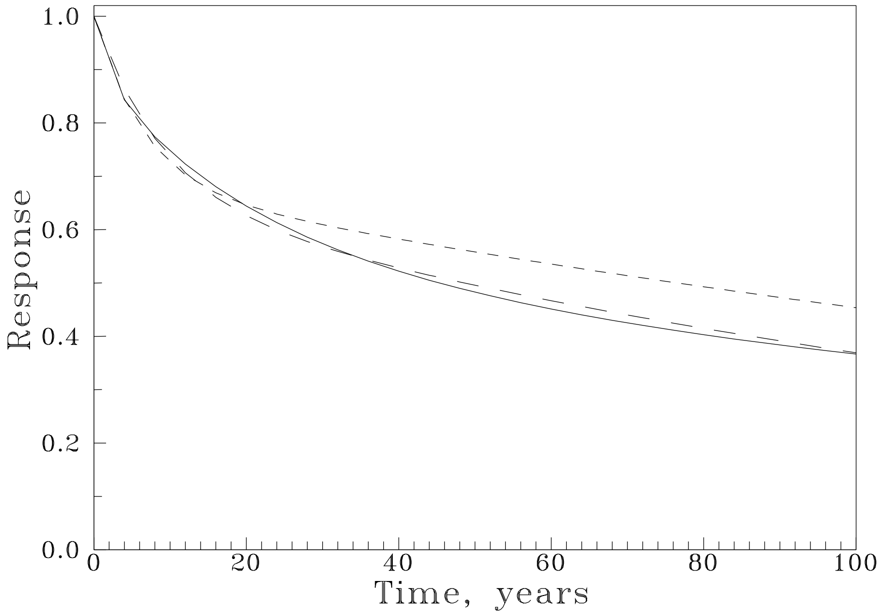

Figure 7: Response functions describing the oceanic uptake of CO_2. The solid curve is the expression (eqn 4) given by Maier-Reimer and Hasselmann (1987). The long dashes give the approximation defined by a sum of two exponentials (eqn 26), calculated as described in Appendix B. The short dashes are an approximation, using 2 exponentials (eqn 29), to the response function of the box-diffusion model used for the IPCC calculations.

Appendix B shows how it is possible to calculate a sequence of multi-exponential approximations for the box-diffusion model as a function of the model parameters. Figure 7 shows the response function from Maier-Reimer and Hasselmann, together with a 2-exponential approximation which agrees quite closely. Also shown is a 2-exponential approximation to the response function of the box-diffusion model used in the IPCC calculations.

Appendix C describes ways in which response functions describing oceanic CO_2 uptake can be transformed to give a combined response functon describing both ocean uptake and CO_2-induced growth.

4d. Statistical modelling

The discussion in the preceding subsections shows that a simulation model is not essential for calculating future CO_2 concentrations. The mathematical models described by ρ, τ or $R(t)$ can be used, with increasing domains of applicability, to calculate CO_2 concentrations. In practice, however, the numerical values used for ρ, τ or $R(t)$ are usually derived from simulation models, either numerically or through analytic techniques such as those described in Appendix B below.

An approach that steps back from this use of simulation models is the statistical modelling of the CO_2 record. Such analyses have been presented by several workers (eg. Surendran and Mulholland, 1986, 1987; Mulholland et al., 1987). It is worthwhile trying to assess the predictive power of such approaches.

> *Statistical fits to the CO_2 record:* The simplest types of statistical analysis of CO_2 records use statistical techniques to fit some form of mathematical representation of $C(t)$. This could be through some form of regression fit using standard functions or through a 'Box-Jenkins' type of model in which $C(t)$ is regarded as the result of some intrinsic equations describing its time evolution, combined with some stochastic contributions. The limitation of statistical modelling based on the CO_2 series alone is that its validity is conditional on the forcing functions (i.e. the CO_2 sources) having the same characteristics in the future as they had in the past. This severely restricts the validity of such modelling for predicting future CO_2 concentrations and completely precludes the use of such models in comparing release modification strategies.
>
> *CO_2 as a response to inputs:* This type of statistical modelling seeks to extend the domain of validity by considering the statistical relation between the CO_2 concentrations and the sources. This approach corresponds to a statistical version of the mathematical models noted above. As with the mathematical modelling, the statistical modelling can be done with varying degrees of sophistication. Relating concentrations and sources at a single time, as for example in a regression fit of $C(t)$ in terms of $S(t)$, is a statistical version of assuming a constant airborne fraction ρ. In principle a better fit should be given by a model where the effects of past inputs influenced $C(t)$ but with exponentially decreasing importance as time progressed. This corresponds to the assumption of a single atmospheric lifetime, τ. Finally, it is possible to build relatively simple statistical models that

represent more general response functions $R(t)$ in terms of sums of exponentials. Some statistical studies of this type were described by Enting (1989). In principle, the predictions from this approach should be as good as those of a simulation model and in addition have a better description of the statistical errors. In practice, the potential of this approach has not been exploited.

5. Calculations

5a. IPCC calculations

The scenario calculations presented in the IPCC report were in two groups: 'policy' scenarios and 'science' scenarios. The 'policy' scenarios were designed to illustrate the consequences of various possible strategies for reducing emissions. The 'science' scenarios were designed to illustrate various aspects of the response of the carbon cycle to changing emission patterns. The IPCC report attributes many of the calculations to the model of Enting and Pearman (1987), however, as discussed in appendix A below, the model that was used could more accurately be described as a modified version of the box-diffusion model of Oeschger et al. (1975). Indeed for the purposes of calculating CO_2 concentrations, the formulation of the model is almost exactly as described by Oeschger et al. (1975) and Siegenthaler and Oeschger (1987) — only the choice of parameters differs. The other modifications made by the present author mainly affect the way in which the model treats the minor isotopes (^{13}C and ^{14}C) of carbon. The IPCC report does not specify the model used for some of the scenario calculations, but the results quoted appear to be those calculated using the box-diffusion model or some equivalent model.

Figure 1.7 (p. 15) of the IPCC report shows the results of 6 of the 'science' scenarios:

a: immediate reduction of emissions to zero from 1990 onwards. In this case CO_2 concentrations decline slowly but are still well above 1960 levels in the year 2100. The details of this result should be treated with caution as it involves instantaneous changes while the models were designed for changes on decadal time-scales.

b: a 2% per year decrease in emissions from 1990 onwards. In this case concentrations grow slowly through the early part of next century and decline very slowly through the latter part of the century, having peaked at just below 400 ppmv.

b: again a 2% per year reduction, but in this case the reduction is delayed to the year 2010 after a continuation of 2% per year growth from 1990 to 2010. In this case concentrations peak at around 460 ppmv towards the end of next century. This illustrates the effect of delaying the implementation of reduction strategies.

c: emissions held constant from 1990 onwards. Concentrations continue to rise, reaching around 520 ppmv (i.e. somewhat less than double pre-industrial levels) in the year 2100.

c′: emissions held constant at 2010 levels after a 2% per year growth from 1990 to 2010. Concentrations reach double pre-industrial levels around 2080 and are over 600 ppmv well before 2100. Again this illustrates the effect of delaying the implementation of reduction strategies.

d: a 2% growth in emissions from 1990 onwards. Doubling occurs before 2050 and a tripling of pre-industrial levels occurs around 2070. While this is the most extreme growth rate considered, the most recent data (CDIAC, 1990) plotted in Figure 4, suggests a current growth rate for CO_2 emissions of around 3.5% per annum.

Cases b and b′ are repeated in Figure A.5 (page 334) of the IPCC report and while plotted differently, the results appear to be the same as from Figure 1.7. The same two cases are also replotted, apparently from the same model calculations, in Figure 4 (p. xvii) in the policymakers' summary of the IPCC report.

Figure A.4 (page 334) gives the results of two 'science' scenarios in which emissions from 1990 on are held constant, in the first case at 1990 levels and in the second case at 50% of 1990 levels. In each case CO_2 concentrations continue to grow throughout next century. Again, while the IPCC report does not specify the model, the results for these cases agree with those of the box-diffusion model. These two cases are replotted in Figure 4 (p. xvii) of the policymakers' summary.

Figure 1.8 (p. 15 of the IPCC report) gives results from two 'science' scenarios in which the concentration histories were specified and the requisite emission histories deduced from the model. The first case had concentrations stabilised at 420 ppmv by the year 2100. This required an initial freezing of emissions at 1990 levels followed by a slow reduction to about 50% of 1990 levels by 2050 and to 30% of 1990 levels by 2100. In the second case, achieving an immediate stabilisation of CO_2 at 1990 levels required an immediate reduction of emission to less the 40% of 1990 levels and a further reduction to around 20% of 1990 levels early next century. It should be emphasised that models such as the box-diffusion model aim to represent the carbon cycle on decadal time scales and that calculations involving instantaneous changes in emission rates will be less accurate than those involving slower changes.

The IPCC report also presents the CO_2 concentrations arising from the four 'policy' scenarios. These are presented in Figure 5 (p. xix) and Figure A.3 (p. 333). The box-diffusion model was applied to three of these 'policy' cases — the results were similar (but not identical) to those presented in the report.

5b. Further calculations

The IPCC science scenarios give a comprehensive coverage of the types of reduction in CO_2 growth that result from various emission reduction scenarios. However, since the Toronto meeting adopted the specific goal of a 20% reduction in fossil fuel emissions relative to 1988 levels by the year 2005, it is worthwhile presenting calculations for this case. To fill in the details,

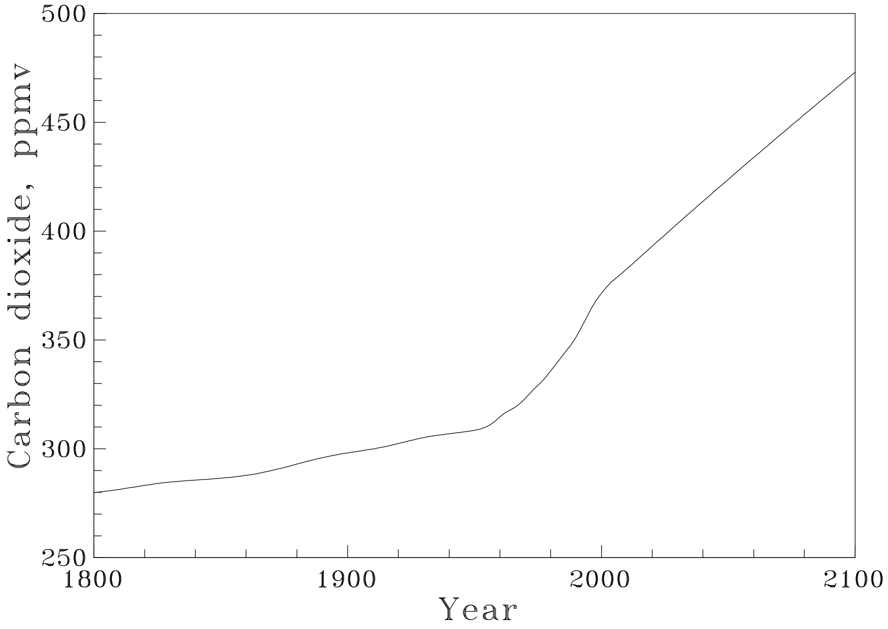

Figure 8: CO_2 concentrations predicted by the box-diffusion model assuming a 20% reduction in CO_2 emissions, relative to 1988, is achieved by 2005, as adopted by the Toronto meeting.

we use the form adopted for planning purposes by the Australian government, where the 20% reduction is preceded by a return to 1988 emission rates by the year 2000. More specifically we assumed a 4% per annum growth for 1989 to 1994, a 3.9% per annum decrease for 1995 to 2000 and a 4.4% per annum decrease for 2001 to 2005 and constant emissions thereafter.

The results are plotted in Figure 8 and show that under this scenario, CO_2 concentrations would continue to rise, but much more slowly than if no emission reductions occur.

6. Feedbacks

6a. Processes

Section 1.2.7 of the IPCC report considers a number of feedback processes that might be expected to influence future atmospheric CO_2 levels. These processes were not included in the calculations of future CO_2 concentrations. The processes listed were:

i. the effect of ocean circulation changes on mixing of carbon into the deep oceans;

ii. the effect of changes in ocean circulation on the marine biota through changes in nutrient supply;

iii. the effect of changing sea surface temperatures on CO_2 partial pressures;

iv. the effect of changed wind patterns on air-sea gas exchange;

v. the effect of increased UV-B radiation on the marine biota;

vi. increased growth of land plants due to the availability of more CO_2;

vii. changes in the terrestrial biomass due to eutrophication and toxification of ecosystems;

viii. direct effects of climate on terrestrial ecosystems;

ix. changes in distribution of vegetation in response to climatic impacts;

x. the effect of increased UV-B on terrestrial vegetation.

Section 1.2.7 (and its various subsections) of the IPCC report gives a qualitative discussion of these various feedback processes, together with estimates of their potential importance. The report's concluding remarks on the question are: *Some of the feedbacks are potentially large and could significantly influence future CO_2 levels. They are difficult to quantify but it seems likely that there would be a net positive feedback, i.e., they will enhance the manmade increase. On the longer term, the possibility of unexpected large changes in the mechanisms of the carbon cycle due to human-induced change in climate cannot be excluded.*

For the present we consider the question of what would be required to include these feedback processes in carbon cycle models, following the numbering of the list above.

i, ii The most serious concerns regarding feedback processes relate to the effect of ocean circulation changes on the global carbon cycle, either directly, through changes in ocean mixing, or indirectly, through effects on the marine biota. The concern is motivated by data suggesting that the cold conditions in glacial times were enhanced by the ocean adopting a different circulation pattern to the present one. More seriously it appears that the atmosphere/ocean system has two quasi-stable states corresponding to glacial and inter-glacial periods. The ocean circulation seems to alternate between these states rather than there being a continuous variation in possible circulation processes. The changes can occur very rapidly (Broecker, 1989). While existing ocean models can give qualitative explanations of the two states, they cannot predict them *a priori* and so cannot reliably answer the question of whether there might be additional quasi-stable states that might be reached through an abrupt jump in response to anthropogenically-induced climate change passing through some threshhold. In view of the uncertainties involved, Broecker (1987) has described the continuing release of greenhouse gases as like *[playing] Russian roulette with climate, hoping that the future will hold no unpleasant surprises. No one knows what lies in the active chamber of the gun . . .*

iii The effect of increased sea-surface temperature is quantifiable in present models. The model described by Enting and Pearman (1987) included the role of sea-surface temperature explicitly, and a number of calculations of SST effects were undertaken. No details of the results were published because the effect was found to be small. The IPCC report quotes a modelling study by Lashof (1989) is showing that the SST feedback may lead to a 5% enhancement in CO_2 concentrations.

iv Changes in sea-surface winds do not affect the gas exchange rate as such, but rather the coefficient relating the gas exchange rate to the CO_2 partial pressure difference between the atmosphere and the ocean. As noted in section 3a, if this exchange coefficient decreased, then atmospheric CO_2 levels would rise slightly, increasing the partial pressure difference, until the gas exchange rate was re-established at essentially the same level as before. An alternative way of understanding this is to note that atmospheric CO_2 is very nearly in equilibrium with the ocean surface — it is the rate of mixing into the deep oceans rather than the air-sea gas exchange rate that determines the long-term rate of increase of CO_2.

v,x Modelling the effects of UV-B requires a scenario for the release of ozone-depleting chemicals (mainly chlorofluorocarbons) since, as noted above, these UV-B effects represent distinct anthropogenic influences on greenhouse gases, rather than being a feedback from climatic changes. Given such a release scenario, atmospheric chemistry models can be used to calculate projected ozone depletions, from which changes in UV-B can be determined. The extent to which this can be prevented will depend on the success of the Montreal Protocol in achieving reductions in ozone-depleting compounds. However, major uncertainties exist concerning the effects of UV-B on the ecosystem level, particularly for marine ecosystems. Predictive modelling, as opposed to exploring possibilites, seems a rather distant prospect.

vi Predicting the extent to which increased atmospheric CO_2 will lead to increased biomass, requires the extrapolation of short-term laboratory studies to give a global-scale description valid for decadal time scales. A number of carbon cycle models have included the effect of CO_2-induced growth, but the parameterisations are uncertain except to the extent that laboratory values are expected to be upper bounds for the global effect. Kohlmaier et al. (1987) have described a more detailed model of the effect of increased CO_2 on the global biomass.

vii, viii, ix Predictive modelling of biomass changes due to climatic influences on ecosystems also seems a distant possibility — again the difficulty is one of ecosystem modelling — extending the domain of existing models so that they are still applicable under changed conditions, while simultaneously expanding the scope of such models to cover the whole of the biosphere. This expanded modelling is however being attempted — see for example King et al. (1989) — and is one of the goals of the International Geosphere-Biosphere Program.

6b. Detection of feedbacks

The discussion in the previous subsection gives only a brief account of the difficulties involved in analysing climate-related feedbacks, but it brings out the main points that we are not in a position to make quantitative predictions about such effects as impacts of UV-B on the biota, impacts of climate on the biota and, perhaps most importantly, variations in the mode of circulation of the oceans.

While the ongoing reasearch into the various processes involved, particularly in the context of the International Geosphere-Biosphere Program (IGBP), will improve this situation, it seems probable that some (perhaps many) of the feedback processes will only be quantified as they occur and have sufficient impact to significantly perturb the global carbon cycle by measurable amounts. At that point, measurements of the extent to which carbon cycle quantities depart from what is predicted in the absence of feedback may help quantify the feedback processes.

From the point of view of the carbon cycle the relevant quantities to monitor are:

i Oxygen levels as a measure of biotic production, both terrestrial and marine.

ii Changes in ^{13}C as a measure of productivity of the terrestrial biota.

iii Levels of ^{14}C as a measure of gross CO_2 uptake rate by the oceans and the terrestrial biota.

iv Spatial distributions of CO_2 (and ^{13}C) in order to deduce the spatial distribution of sources and sinks.

v Further measurements of ocean chemistry in order to obtain a direct estimate of net ocean CO_2 uptake.

The principle used here is one of checking to see if all the measureable aspects of the carbon cycle are consistent with a ‘neutral’ description, and interpreting anomalies in terms of additional processes.

In order to achieve this, we need a better understanding of how the ‘natural’ carbon cycle works. In the words of Keeling (1988), although *the earth is still basically healthy . . . One cannot possibly understand the disease unless one understands what it means to be healthy. We have probably only a few more decades to study a ‘healthy’ earth.* The present lack of a consistent description of the global carbon cycle indicates either that the present modelling base is inadequate as a basis for detecting CO_2-climate feedbacks or, less probably, that some such feedback is already operating.

7. Summary

The preceding sections of this report have described the basis of calculations of future concentrations of atmospheric CO_2. It has been emphasised that these projections are subject to two important classes of caveat:

i. At present, it is not possible to take into account possible feedback processes such as those in which climatic changes resulting from increased CO_2 act to perturb the operation of the global carbon cycle. In particular, there is a possibility that the ocean circulation may change abruptly into some new mode of dynamical behaviour in response to climate change, and that chemical and climatic feedbacks may serve to stabilise this behaviour. It appears probable that some such feedback loop was associated with glacial-to-interglacial changes. The type of change or the probability of it happening are beyond our current predictive capability.

ii. It has not been possible to obtain a fully-consistent description of the current operation of the global carbon cycle. Different types of evidence suggest rather different atmospheric carbon budgets. Until this problem can be resolved, there remains a strong possibility that it is not accurate to model the atmospheric carbon budget on the assumption that the oceans are the major carbon sink.

The regularity of the observed increase of atmospheric CO_2 (see Figures 1 and 2) makes it seem unlikely that the discrepancies mentioned in [ii] are actually due to having feedback processes already perturbing the global carbon cycle. Similarly, if the main sink of atmospheric CO_2 is due to CO_2-induced biotic growth rather than oceanic uptake, then the regularity of the increase in CO_2 implies that we can calculate future CO_2 concentrations assuming a continuing sink, even if we are unsure about the nature of the sink. In the medium to long term, a biotic sink would have different response characteristics to an oceanic sink and so misintepreting the nature of the sink would distort predictions beyond a few decades. Clearly further research is needed in order to reduce these uncertainties.

To summarise: predictions of future atmospheric CO_2 concentrations arising from specified releases over the next century are reasonbly reliable subject to two important caveats. It is assumed that the work of Tans et al. (1990) does not really imply a major deficiency in the conventional view of the atmospheric carbon budget and is is assumed that the operation of the global carbon system will not be disrupted be major changes in the mode of circulation of the oceans.

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Notes on the electronic edition

The electronic edition was prepared from the LaTeX files used to produce the B5 format print edition, converted to the CSIRO Atmospheric Research post-1998 A4 style (electronic version). The cover figure has been replaced with Figure 8, an incorrect figure reference has been corrected, a ‘submitted’ publication reference has been filled in, and several spelling errors corrected.

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Appendix A — Some details of the IPCC calculations

The IPCC report attributes a number of the scenario calculations to the models described by Enting and Pearman (1987) (and references therein). A more accurate description of the model would be to describe it as being based on the box-diffusion model of Oeschger et al. (1975) with a number of enhancements including some used in the box-diffusion model by Siegenthaler and Oeschger (1987) and some used in the related model of Enting and Pearman (1987).

The special features of the box-diffusion model used for the IPCC calculations are:

i. An explicit stratospheric reservoir, primarily for modelling the atmospheric response to ^{14}C from nuclear tests;

ii. An explicit representation of the terrestrial biota;

iii. Inclusion of marine detrital fluxes, so that the vertical gradients in ocean carbon concentration can be modelled.

The key parameters describing the oceanic uptake of CO_2 were

Deep ocean diffusion The parameter K was set to 5364 m^2y^{-1}.

Atmospheric turnover time This corresponds to κ^{-1} and was taken as 8.88 yr. (The turnover time is defined as the atmospheric carbon content divided by the gross air-to-sea carbon flux).

Buffer factor This uses the formalism of Bacastow (1981) including non-linear contributions.

The inclusion of the stratosphere has a minor effect on the tropospheric response to CO_2 inputs. Other model parameters such as those specifying detrital fluxes will affect the carbon isotope distributions but do not directly affect the CO_2 uptake in the model. The other parameters become important when isotopic data, particularly ^{14}C distributions, are commonly used to tune the parameters K and κ. The results of such tuning will depend on how other model parameters are determined. For the IPCC calculations it was decided to use values given above for K and κ since these were based on estimates not involving carbon cycle data. The carbon isotope data could then be used to confirm the validity of the parameters. The estimates were taken from Broecker et al. (1980) with K being based on oceanic uptake of tritium (^{3}H) from thermonuclear weapon tests and κ being based on air-sea exchange of radon.

Appendix B — Approximating response functions

In section 4, it was suggested that sums of exponentials were a desirable way of approximating response functions. The advantages of this approach include:

i. ease of description;

ii. ease of integration when calculating concentrations;

iii. the ease with which relations between response functions, including explicit inversion relations for deconvolutions, can be calculated;

iv. the close relation to statistical analysis techniques based on Kalman filtering.

The simplification of the integations is particularly noteworthy. The basic relation is

$$Q(t) = C(t) - C(t_0) = \int_{t_0}^{t} R(t - t')\, S(t')\, dt' \tag{5}$$

Formally this requires a separate time integration over the range t_0 to t for each time t. However if we have

$$R(t) = \sum A_j \exp(-\alpha_j t) \tag{6}$$

then we can put

$$Q(t) = \sum Q_j(t) \tag{7}$$

with

$$Q_j(t) = \int_{t_0}^{t} A_j \exp(-\alpha_j(t - t'))\, S(t')\, dt' \tag{8}$$

This leads to the relation

$$\begin{aligned} Q_j(t+\Delta) &= A_j \int_{t}^{t+\Delta} \exp(-\alpha_j(t+\Delta-t'))\, S(t')\, dt' \\ &+ A_j \exp(-\alpha_j\Delta) \int_{t_0}^{t} \exp(-\alpha_j(t-t'))\, S(t')\, dt' \qquad (9) \\ &= \exp(-\alpha_j\Delta) Q_j(t) + A_j \int_{0}^{\Delta} \exp(-\alpha_j x)\, S(t+x)\, dx \qquad (10) \end{aligned}$$

Using this formula, the Q_j can be constructed at any desired interval Δ with each additional value requiring only an integral over a time interval of Δ. The calculation can thus be undertaken on virtually any personal computer and, more tediously, even on a hand calculator. Hand calculation is possible in special cases particularly if one uses analytic approximations to the fossil fuel release such as:

$$\begin{aligned} F(t) &\approx 97.867 \times 10^{12} \times \exp(0.04189(t - 1860)) \qquad \text{for } 1860 \le t \le 1914 \\ &\approx 838.82 \times 10^{12} \times \exp(0.01411(t - 1914)) \qquad \text{for } 1914 \le t \le 1947 \\ &\approx 1467.67 \times 10^{12} \times \exp(0.04396(t - 1947)) \qquad \text{for } 1947 \le t \le 1980 \qquad (11) \end{aligned}$$

from Pearman (1980). An alternative way of simplifying the integrations is to differentiate the definition of Q_j with respect to time to give

$$\dot{Q}_j(t) = A_j S(t) - \alpha_j Q(t) \tag{12}$$

whence

$$Q_j(t) = A_j \int_{t_0}^{t} S(t')\,dt' - \alpha_j \int_{t_0}^{t} Q_j(t')\,dt' \tag{13}$$

The construction of inversion relations for deconvolving concentration histories was discussed by Enting and Mansbridge (1987). Given the relation:

$$Q(t) = \int_{t_0}^{t} R(t-t')\,S(t')\,dt' \tag{14}$$

there is an inversion relation:

$$S(t) = \dot{Q}(t)/R(0) - Q(t)\dot{R}(0)/R(0)^2 - \int_{t_0}^{t} K(t-t')\,Q(t')\,dt' \tag{15}$$

If $R(t)$ is a sum of N exponentials then the inversion kernel $K(t)$ is a sum of $N-1$ exponentials. The relation between $R(t)$ and $K(t)$ is best described in terms of Laplace transforms — see Enting and Mansbridge (1987) for further details.

Given these advantages it is worthwhile considering the ways in which response functions can be represented by sums of exponentials. In many cases the representation may be non-unique — a classic example is given by Lanczos (1988, p278). The approach that we use for fitting exponentials is based on the analysis by Yeramian and Claverie (1987) which used Laplace transforms. The Laplace transform of the response function is defined by

$$r(p) = \int_{0}^{\infty} R(t)\,e^{-pt}\,dt \tag{16}$$

The method of Yeramian and Claverie involves expanding the Laplace transform about a particular value p_0 as a Taylor's series in powers of $x = (p - p_0)$. We use $p_0 = 0.04$ so that the approximation agrees with the model response function for releases growing at 4% per annum which is characteristic of fossil fuel releases over much of the industrial period (see Figure 4). One chooses an approximation:

$$R(t) \approx \tilde{R}(t) = \sum_{j=1}^{N} A_j \exp(-\alpha_j t) \tag{17}$$

whence

$$r(p) \approx \tilde{r}(p) = \sum_{j=1}^{N} \frac{A_j}{p+\alpha_j} = \sum_{j=1}^{N} \frac{A_j}{x+\beta_j} \tag{18}$$

where $\beta_j = \alpha_j + p_0$. On then chooses the approximation so that, at p_0, the transform, $r(p)$ and the approximation $\tilde{r}(p)$ are equal, as are their first $2N-1$ derivatives with respect to p. The derivatives of $r(p)$ can be obtained numerically from data for $R(t)$ as described by Yeramian and Claverie (1987) or analytically as in the examples below.

The case of 2 exponentials constrained so that $R(0) = 1$ can be solved analytically. The constraint on $R(0)$ means that only $r(p_0)$ and its first two derivatives are required. One has

$$\tilde{r}(p) = \frac{A}{x+\beta_1} + \frac{1-A}{x+\beta_2} \tag{19}$$

Putting $\gamma_j = 1/\beta_j$, one has

$$\tilde{r}(p_0) = k_0 = \gamma_2 + A(\gamma_1 - \gamma_2) \tag{20}$$

$$-\frac{d\tilde{r}}{dp}(p_o) = k_1 = \gamma_2^2 + A(\gamma_1^2 - \gamma_2^2) \tag{21}$$

$$\frac{1}{2}\frac{d^2\tilde{r}}{dp^2} = k_2 = \gamma_2^3 + A(\gamma_1^3 - \gamma_2^3) \tag{22}$$

After some manipulation, γ_2 is found as a solution of

$$k_2k_0 - k_1^2 - \gamma_2(k_2 - k_1k_0) + \gamma_2^2(k_1 - k_0^2) = 0 \tag{23}$$

with

$$\gamma_1 = \frac{k_1 - \gamma_2^2}{k_0 - \gamma_2} - \gamma_2 \tag{24}$$

and

$$A = \frac{k_0 - \gamma_2}{\gamma_1 - \gamma_2} \tag{25}$$

The expression given by Maier-Reimer and Hasselmann (1987), (equation (4) of section 4c above) can be approximated by two exponentials as

$$R(t) \approx 0.392\exp(-t/10.795) + 0.608\exp(-t/380.574) \tag{26}$$

The approximation and the full expression are shown for comparison in Figure 7. It will be seen that, over the 100-year time span, the 2-exponential approximation follows the original curve very closely.

For the box diffusion model, Enting (1990) derived

$$r(p) = \left(p + \frac{\kappa}{1+\kappa Z\xi m(p)}\right)^{-1} \tag{27}$$

where

$$m(p) = \left[p + \frac{\sqrt{pK}}{d_{\rm m}}\tanh\left(L\sqrt{\frac{p}{K}}\right)\right]^{-1} \tag{28}$$

is the Laplace transform of the response function describing the response of the ocean surface mixed layer to fluxes of carbon from the atmosphere. (The exponent -1 was erroneously omitted from the expression for $m(p)$ given by Enting, 1990). In these expressions, $d_{\rm m}$ is the mixed layer depth, taken as 75 m; L is the remaining ocean depth, taken as 3725 m; ξ is the buffer factor taken as 9.36 (plus non-linear corrections) in the IPCC calculations; and Z is the ratio of pre-industrial carbon contents of the atmosphere and mixed layer, taken as 0.905.

The box diffusion model reponse function can be differentiated and the results substituted into the 2-exponential approximation to give analytic expressions for an approximate $R(t)$ in terms of the parameters of the box-diffusion model. However the results would be too complex to be particularly enlightening. Numerical solution is more appropriate. Using the parameters K = 5346 m^2 yr^{-1} and κ^{-1} = 8.88 yr as in the IPCC calculation leads to an approximate response function

$$R(t) \approx 0.314 \exp(-t/6.496) + 0.686 \exp(-t/241.45) \tag{29}$$

This approximation is plotted in Figure 7 above.

Appendix C — Combining response functions

In appendix B, one of the advantages claimed for the use of response functions expressed as sums of exponentials was the ease of transforming the expressions to produce related response functions. The derivation of the explicit inversion relation by Enting and Mansbridge (1987) is an example of this. In this appendix we analyse the way in which a response function describing oceanic uptake of CO_2 is modified to produce a response function describing the combined effects of oceanic uptake and CO_2-induced plant growth. The atmospheric mass balance is defined by

$$\dot{C}(t) = S(t) + \Phi(t) - G(t) \tag{30}$$

where C is the atmospheric CO_2 content, S is the anthropogenic source, Φ is the net oceanic uptake of CO_2 and G is the rate of CO_2-induced plant growth. The extra growth is modelled following Kohlmaier et al. (1987) as

$$G(t) = P_0 \left(1 + \frac{\beta Q(t)}{C(t_0)}\right) - \frac{B(t)}{\tau} \tag{31}$$

where B is the terrestrial biomass, Q is $C(t) - C(t_0)$, P_0 is the 'natural' value of the net primary production, τ is a mean biotic turnover time and the degree of CO_2-induced growth is described by the so-called 'beta-factor', β. If we wish to consider deforestation effects, we need to focus on the extra biomass $D(t)$ due to CO_2-induced growth and write

$$G(t) = \dot{D}(t) = \frac{P_0 Q(t) \beta}{C(t_0)} - \frac{D(t)}{\tau} \tag{32}$$

If we let $q(p)$, and $d(p)$ be the Laplace transforms of $Q(t)$ and $D(t)$ and $r(p)$ be the Laplace transform of the response function describing oceanic uptake we have

$$pd = \gamma q - d/\tau \tag{33}$$

where $\gamma = P_0 \beta / C(t_0)$ and

$$q(p) = r(p)(s - pd(p)) \tag{34}$$

describing the oceanic reponse to the combined source $S(t) - \dot{D}(t)$. From these equations one has

$$d = \frac{\gamma q(p)}{p + 1/\tau} \tag{35}$$

and thence

$$q = \left(\frac{(p + 1/\tau)r(p)}{p + 1/\tau + p\gamma r(p)} \right) s(p) \tag{36}$$

so that the expression on the right hand side, multiplying $s(p)$ is the Laplace transform of the function describing the way in which the atmosphere responds to anthropogenic inputs, given the combined effects of oceanic uptake and CO_2-induced growth. Simple substitution shows that if $R(t)$ is approximated as a sum of N exponentials so that $r(p)$ is a ratio of polynomials of degree $N - 1$ and N in p, then the combined Laplace transform is a ratio of polynomials of degrees N and $N + 1$ so that the combined response function is a sum of $N + 1$ exponentials.

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