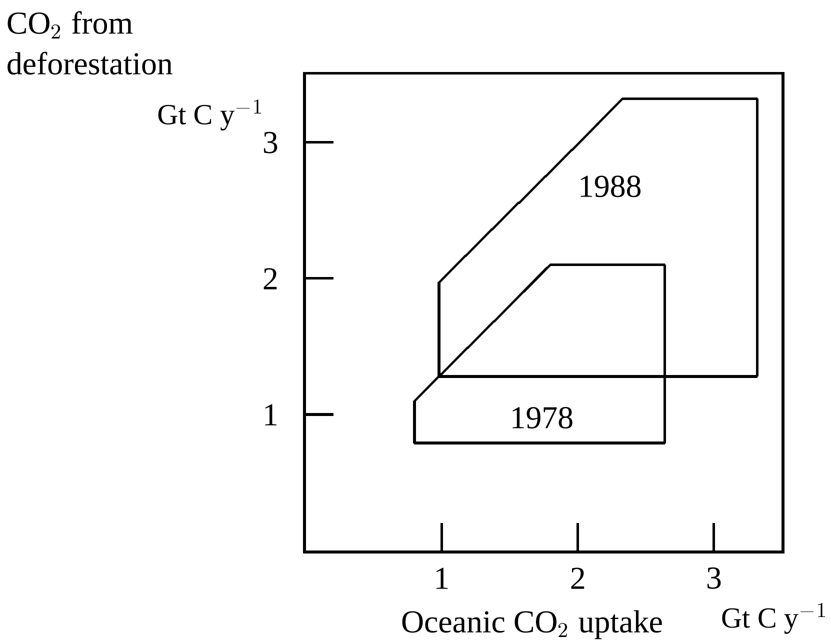
Constraining the Atmospheric Carbon Budget: A Preliminary Assessment

I.G. Enting

Mutually consistent CO_2 flux ranges showing change over a decade.



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Address and contact details: CSIRO Atmospheric Research
Private Bag No.1 Aspendale Victoria 3195 Australia
Ph: (+61 3) 9239 4400; fax: (+61 3) 9239 4444
e-mail: chief@dar.csiro.au

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Constraining the Atmospheric Carbon Budget: A Preliminary Assessment

I.G. Enting
CSIRO Atmospheric Research
Private Bag 1, Aspendale,
Vic 3195, Australia

1. Introduction

Direct observations show that the concentration of CO_2 in the atmosphere has been increasing over the last three decades (from about 315 ppmv in 1959 to 350 ppmv in 1990) and that the rate of increase has grown. Measurements of gas trapped in bubbles in polar ice show that the concentrations were around 280 ppmv at the beginning of the last century and have grown at a generally increasing rate over the last two hundred years. The current rate of increase of atmospheric CO_2 represents about half of the rate at which carbon is released due to the use of fossil fuels.

While it is generally assumed that the world's oceans represent the sink for much of the fossil carbon that leaves the atmosphere, the role of the terrestrial biota in the atmospheric carbon budget is the subject of considerable uncertainty. In particular, the study by Tans et al. (1990) raised the possibility that the oceanic uptake of CO_2 might be only half as much as determined by conventional carbon cycle modelling, implying very large biotic uptakes.

Emissions	Gt C y^{-1}
Fossil carbon release	5.4 ± 0.5
Deforestation and land use change	1.6 ± 1.0
Accumulation in atmosphere	3.4 ± 0.2
Uptake by ocean	2.0 ± 0.8
Net imbalance	1.6 ± 1.4

Table 1: Atmospheric carbon budget for 1980–90, from IPCC (1990, p13).

Table 1 presents the estimated atmospheric carbon budget for the period 1980–90 as presented in the IPCC (1990) report. Given recent developments in carbon cycle studies it seems appropriate to refine this presentation in a number of ways:

i. Explicitly recognising the possible role of extra CO_2-induced growth of the terrestrial biota, even if direct estimates have much greater uncertainties than those arising from atmospheric carbon budgeting.

ii. A greater recognition of the fact that the budget is changing in response to anthropogenic inputs. The changes over the decade 1980–1990 have been comparable to the uncertainties in some components of the budget and a comprehensive analysis needs to separate actual uncertainties from secular changes.

iii. A recognition that some of the doubts raised by Tans et al. (1990) appear to have been resolved.

iv. A more systematic treatment of the range of uncertainty.

It must be emphasised that an understanding of the current atmospheric carbon budget confers only a limited predictive power for estimating the future atmospheric CO_2 levels resulting from various possible anthropogenic emissions. Among the possible changes that will be neglected are:

- Direct effects on CO_2 uptake from changes in ocean circulation that result from either natural or anthropogenic climate change;
- Indirect effects of such circulation changes due to changed nutrient supply to the marine biota.
- Direct effects of climatic change and changes UV-B on the marine and terrestrial biota.

Concerns such as these are noted in Section 1.2.7 (and subsections thereof) of IPCC (1990).

The present report has the following aims:

i. Presenting the methodology for using linear programming techniques to analyse atmospheric constituent budgets, for use by those working on different aspects of the global carbon cycle.

ii. Presenting a specific set of estimates of the limits on the atmospheric carbon budget, within the present state of knowledge of global constraints.

iii. Presenting preliminary analyses of the limits on the atmospheric carbon budget based on regional carbon constraints, incorporating the results of atmospheric transport modelling.

The estimated carbon budgets will be presented at three levels of detail. Each step represents the inclusion of additional indirect information, thus tightening the constraints, but it also involves additional assumptions about the correctness of the interpretations placed on such indirect information.

The three levels of detail are:

i. Direct estimates of each of the main contributions to the atmospheric carbon budget. These are described in Section 2 and used in Section 3 to illustrate the linear programming formalism.

ii. The use of ocean models to estimate the oceanic uptake of CO_2. The various approaches are discussed in Section 4.

iii. The use of regional carbon budgets derived from analysing spatial distributions of CO_2 using atmospheric transport models. The possibilities and data requirements are discussed in Section 5.

In order to take into account the change in the budget over time, we consider three different periods:

1978 As a first point for comparisons.

1988 As a second point to show the changes in the atmospheric carbon budget with time.

1980-5 For comparison with earlier work, especially that based on spatial distributions of CO_2.

The years 1978 and 1988 are used as reference points for the comparisons that illustrate the extent of changes in the atmospheric carbon budget. These are nominal time points for comparison. Since instantaneous rates of change can not be reliably determined from observational data, the figures we use are averages, generally over 2 or more years, normalised to the middle of the reference years 1978 and 1988. The period 1980–5 is the most suitable for looking at the regional budgets because of the greater quantity of data available. Records from before this time are subject to unknown offsets relative to each other because of lack of adequate intercalibration. In many cases records from later periods are yet to be published. However the interpretation of the atmospheric budgets for the period 1980–1985 is complicated by a number of anomalies:

i. The fossil fuel emissions ceased to grow over this period.

ii. The 1982–3 ENSO event had a large effect on CO_2 (see for example Gaudry et al., 1987).

iii. The interhemispheric gradient for this period seems anomalously low, possibly as a consequence of one or both of the other two effects noted.

The outline of the remainder of this report is as follows. Section 2 reviews the global constraints on the atmospheric carbon budget. Section 3 describes the linear programming formalism for analysing the carbon budget and applies the formalism using the constraints from Section 2 as the first example. Section 4 gives a more detailed discussion of model-based constraints on the oceanic uptake of CO_2, reviewing various modelling approaches. The section concludes with an analysis of how, subject to the validity of the model, model-based constraints can constrain the atmospheric carbon budget more tightly than direct estimates alone. Section 5 reviews the role of regional constraints based on atmospheric transport modelling. The results quoted from regional budgeting are purely illustrative because of the simplified nature of the transport model and the ad hoc nature of the error analysis.

2. Global Constraints

For this analysis we regard the atmospheric budget at the specified times as a balance of the 5 components, each denoted by a 6-letter identifier as used in our computer programs:

INCRES This is the rate of increase of carbon (as CO_2) in the atmosphere.

FOSSIL This is the rate of input of fossil carbon

OCEANS This is the net uptake of carbon by the oceans.

CLEARS This is the net carbon input into the atmosphere resulting from land-use changes.

FERTIL This is the amount of extra net biotic growth due to the fertilising effect of CO_2 and any other anthropogenic influences.

Each of these components is expressed in units of Gt C y^{-1}. The following subsections describe the prior constraints that can be placed on each of the components.

2a. The atmospheric increase

In order to define the rate of increase of CO_2 in the atmosphere, consistency of calibration in the observations in extremely important. The primary source of data that we use is the Scripps programs for Mauna Loa and the South Pole (Keeling et al., 1989a). The annual means for Mauna Loa and the South Pole are used, subject to limitations from missing South Pole data.

For '1978' the difference in the 1977 and 1979 annual means implied growth rates of 1.48 ppmv y^{-1} for Mauna Loa and 1.49 ppmv y^{-1} for the South Pole. The 1976 to 1980 difference for Mauna Loa implied 1.64 ppmv per year. We take the '1978' value as 1.5 ± 0.1 ppmv y^{-1} or 3.18 $\pm$ 0.20 Gt C y^{-1}. The 1980 to 1985 difference for Mauna Loa implies a mean growth of 1.4 ppmv y^{-1}, while the 1979 to 1986 difference for the South Pole implies 1.48 ppmv y^{-1}. We take the rate as 1.45 $\pm$ 0.05 ppmv y^{-1} or 3.08 $\pm$ 0.10 Gt C y^{-1}. The range for 1980–1985 is taken as half of the '1978' range because the change is being determined relative to a longer time base.

The '1988' value was estimated from the Scripps South Pole and Mauna Loa data, as published in CDIAC (1991). The respective mean growth rates from these records were 1.98 and 1.73 ppmv y^{-1} for 1987–1989 and 1.74 and 1.57 ppmv y^{-1} for 1986–1990. We take the value 1.76 $\pm$ 0.20 ppmv y^{-1} which gives a range of 3.32 to 4.16 Gt C y^{-1}. The larger range compared to the '1978' value reflects a possible ENSO influence.

2b. Fossil carbon release

Estimates of the global annual releases of CO_2 from fossil carbon (including cement production) have been compiled by Keeling (1973), Rotty (1987) (and references therein) with recent estimates being collected in CDIAC (1990). The current methodology has been described by Marland and Rotty (1984). G. Marland presented an estimate of 5.967 Gt for 1989 at the NATO Advanced Study Institute (Il Ciocco, Italy, September, 1991). For the purposes of the present analysis we use 5.14 Gt C y^{-1} for 1978 and 5.86 Gt C y^{-1} for 1988, representing the averages (weighted as ($\frac{1}{4}$, $\frac{1}{2}$, $\frac{1}{4}$)) for 1977–1979 and 1987–1989 respectively. The figure 5.20 Gt C y^{-1} is used as the average for the period 1980–1985.

The uncertainty ranges applied to these estimates are $+10$% and -5% in the reference case. Some examples given below explore the consequences of reducing the range to $+5$% to -2.5%.

2c. Ocean uptake

Currently, direct measurements of CO_2 fluxes over the ocean, using gradient techniques, are possible only in favourable conditions. Thus no global (or even regional) coverage has been achieved in this way.

The most direct estimates of air-sea flux of CO_2 are those that combine measurements of the CO_2 partial pressure difference (Δp_{CO2}) with a gas-exchange coefficient to produce a CO_2 flux.

Such calculations are subject to three important limitations:

- The lack of p_{CO2} data for the Southern Hemisphere;
- Questions about the representativeness of Northern Hemisphere p_{CO2} data;
- The discrepancy between the air-sea gas exchange coefficients measured directly and those estimated using the global uptake of ^{14}C from weapons tests.

The most comprehensive attempt at direct calculation of oceanic CO_2 uptake was that of Tans et al. (1990). They concluded that the oceanic fluxes were (with uptakes negative) -0.59 Gt C y^{-1} north of 15°N, 1.62 Gt C y^{-1} from 15°N to 15°S, and -2.39 Gt C y^{-1} south of 15°S. These fluxes were calculated using monthly mean wind speeds with an empirical transfer coefficient E (in moles of CO_2 m^{-2} yr^{-1} μatm^{-1}) expressed as a function of windspeed W (in m s^{-1}) as

$$E = 0.016(W - 3) \qquad \text{for } W > 3 \tag{1}$$

$$E = 0 \qquad \text{for } W \leq 3 \tag{2}$$

Tans et al. indicated that use of the alternative transfer coefficients of Liss and Merlivet (1986) would lead to fluxes half of those quoted, implying ranges (-0.59 to -0.30), (1.62 to 0.81) and

(-2.39 to -1.20) for their 'northern', 'tropical' and 'southern' regions. In order to convert these ranges to the latitudinal division used below with a 'tropical' range of 12°N to 12°S, we simply scale the tropical component and add the difference equally to the other two regions, giving (-0.43 to -0.22), (1.30 to 0.65) and (-2.23 to -1.12). Tans et al. suggested that sampling errors could lead to as much as a 1 ppmv bias implying flux errors of up to 0.07 Gt C y^{-1} for northern oceans and up to 0.15 Gt C y^{-1} for southern oceans.

The systematic major adjustments to these ranges are the corrections noted by Sarmiento and Sundquist (1992); the effect of carbon transport by rivers and the effect of 'skin-temperature' on determining air-sea gas exchange. Sarmiento and Sundquist estimate that the carbon flux through river is adding 0.2 to 0.6 Gt C y^{-1} to northern oceans by a transport additional to the surface fluxes calculated by Tans et al., thus changing the 'northern' range to (-1.03 to -0.42). They also suggest that the air-sea exchange will be determined by the temperature of a thin layer at the ocean surface whereas measurements of ocean p_{CO2} are through equilibration of water from a little below the ocean surface. They suggest that this could increase the calculated global uptake by 0.3 to 1.1 Gt C y^{-1} assuming gas exchange rates consistent with oceanic uptake of ^{14}C with about half this correction applying if the lower gas exchange coefficients were used. This leads to a set of flux ranges of (-1.43 to -0.52), (1.00 to 0.55) and (-2.63 to -1.22).

Apart from the sampling errors, most of the corrections have their limits set by the range of uncertainty in the gas exchange coefficient and so the ranges for the three regions do not represent independent variations. It is not consistent to combine the maximum tropical release with the minima of higher latitude uptake or vice versa. The global range corresponds to that obtained from summing the limits of the three ranges to give -2.63 to -1.19 Gt C y^{-1}.

Our final ranges are obtained by applying the 'sampling' error of $\pm$0.3 Gt C y^{-1} globally (as suggested by Tans et al., 1990), leading to a global range of -2.93 to -0.89 Gt C y^{-1}. Applying the 'sampling' error on a regional basis (as 0.07, 0.08, 0.15 Gt C y^{-1}) gives the set of flux ranges (-1.50 to -0.48), (1.08 to 0.51) and (-2.78 to -1.15).

Of the global range of uncertainty (over 2 Gt C y^{-1}), roughly equal contributions come from: uncertainty in the air-sea gas exchange relation, sampling limitations for p_{CO2}, and the systematic corrections for river carbon and skin-temperature effects. Therefore no single improvement will lead to major reductions in the uncertainty over the global net oceanic uptake.

2d. CO_2 release from land-use changes

Houghton et al. (1983) presented a set of calculations of net CO_2 emissions resulting from land use changes for the period 1860–1980. The effects included carbon release from forest clearing either for agriculture or replanting and then the effect of regrowth from re-aforestation, together with other consequent changes, particularly those involving soil carbon.

Recent work by Houghton (personal communication) has produced a pair of estimates of the time history of release. These give the ranges 0.990 to 1.616 Gt C y^{-1} for 1978, 1.194 to 1.991

Gt C y^{-1} for 1980–1985 and 1.594 to 2.550 for 1988. These estimates can probably be regarded as spanning a plausible range rather than the full range of uncertainty. Houghton et al. (1987) typically use a ± 50% uncertainty around their best estimates. In order to produce a comparable range we have taken a lower limit of 80% of the low estimate and an upper limit of 130% of the higher estimate, giving ranges 0.79 to 2.10 Gt C y^{-1}, 0.96 to 2.56 Gt C y^{-1} and 1.28 to 3.32 Gt C y^{-1} for 1978, 1980–1985 and 1988 respectively.

The spatial distribution was discussed by Houghton et al. (1987); the division was 0.028 Gt C y^{-1} for Australia and New Zealand, 1.659 for tropical sources and 0.105 for northern sources, all applicable to 1980. For the present we neglect the fact that a small part of the tropical source (e.g. for Uganda) lies outside the range of 12°S to 12°N used in the regional study below. For the northern and southern regions we apply the ± 50% ranges to give 0.052 to 0.157 Gt C y^{-1} and 0.014 to 0.042 Gt C y^{-1} respectively. We then subtract these from the global range to get the 'tropical' range of 0.90 to 2.36 Gt C y^{-1}.

2e. CO_2 uptake from fertilisation effects

The estimates obtained by Houghton et al. (1983) are of the carbon fluxes from the terrestrial biota occurring as a result of land-use changes. There will be a number of other effects that lead to biotic fluxes even in the absence of land-use changes.

- Increased growth due to the fertilising effect of additional atmospheric CO_2;
- Increased growth due to the fertilising effect of additional anthropogenic nitrogen compounds;
- Decreased carbon stored following damage to biota from other pollution;

Of these effects, the possibility of CO_2-induced growth has attracted most attention. Among the various approaches to quantifying (or at least identifying) this effect have been:

i. Global modelling, using extrapolations of growth factors from laboratory studies (e.g. Kohlmaier et al., 1987);

ii. Interpretation of changes in the seasonal cycle of CO_2 in terms of biotic growth;

iii. Searches for increased growth in tree-rings.

Interpretation of changes in the seasonal cycle of CO_2 in terms of increased biotic uptake is subject to a number of serious problems:

- A change in amplitude of the seasonal exchange does not in itself imply a change in net carbon storage and certainly provides little basis for quantifying the integrated global carbon storage.

- The change in amplitude is not observed as a coherent signal over all observational records.
- The change in amplitude at Mauna Loa seems to have occurred primarily between 1975 and 1980 with no consistent trend either before or after this period (see for example Enting and Manning, 1989). This weakens the claim for an association between amplitude changes and CO_2 changes.
- Contrary to claims by Idso (1987), the correlation structure that Enting (1987) interpreted as a characteristic biotic signal does not imply that the same cause applies to the longer-term change in amplitude. Furthermore a refined analysis (Enting and Manning, 1989) shows that the correlation is confined to the period prior to the increase over 1975–1980. Subsequent analysis of longer records by K. Thoning (personal communication) suggested that the correlation structure was reversed after 1980. Thus the Enting (1987) analysis does not constitute detection of a global-scale fertilisation effect.

The possibilities for detecting a CO_2-fertilisation signal in tree-ring records are severely restricted by the difficulties of separating such a signal from climatic signals, although La March et al. (1984) claimed to have detected a fertilisation signal. In any case, detection of a signal in a single species (at a climatically stressed site) provides an insufficient basis for quantifying the global carbon storage.

For the present study we adopt model-based results as giving the most direct estimates available and in particular we use the results of Kohlmaier et al. (1987). Their main result is an estimated uptake rate of 1.4 ± 0.7 Gt C y^{-1} for 1982. This represents the combination of 0.7 ± 0.3 Gt C y^{-1} stored in living biomass, 0.07 ± 0.03 Gt C y^{-1} stored in litter and 0.60 ± 0.35 Gt C y^{-1} stored in humus. On a 4-biome division, the storage in the living component was quoted as 0.09 to 0.20 Gt C y^{-1} in grasslands, 0.16 to 0.36 Gt C y^{-1} in tropical forests, 0.13 to 0.33 Gt C y^{-1} in temperate and boreal forests and very small amounts in agricultural systems. (The slightly wider range on the total apparently represents a degree of cautiousness on the part of the authors).

In order to estimate the way in which the results from Kohlmaier et al. (1987) can be extended to describe the variation in time and space, a related model developed by P. Polglase of Melbourne University has been used. For a β-factor of 0.2 the model predicted a biotic uptake increasing from 0.48 to 0.66 Gt C y^{-1} over 1975–1985. For $\beta = 0.5$ the increase was from 1.21 to 1.65 Gt C y^{-1}. Therefore to extend the Kohlmaier et al. 1982 value to 1978 and 1988, we apply shifts of -0.1 and $+0.1$ to the lower bound and -0.3 and $+0.3$ to the upper bound, having scaled-up the upper rate-of-change to bring the rates into agreement with the upper estimate of Kohlmaier et al. (1987). The Polglase model was also used to investigate the distribution of uptakes between biomes. For both the upper and lower β values tropical forests were found to contribute close to a third of the total uptake. This is smaller than the 50% fraction applying to the living biomass because of the much smaller component of soil carbon storage calculated for tropical forests.

3. Methodology

3a. General

The analysis of sets of constraints such as those developed in the previous section is handled using a *linear programming* approach.

Note that the term *programming* is used in this context with the meaning (standard in many branches of mathematics) of 'scheduling' and does not specifically refer to computer programming.

The aim of the formalism is to give a way of combining the estimates of the various contributions to the atmospheric carbon budget, together with their uncertainties, in order to give a consistent picture of the final uncertainty remaining after all of the various constraints have been incorporated.

Given a decomposition of the atmospheric carbon budget into a set of components and the formulation of a set of (linear) constraints applying to these components, the linear programming formalism can be used in several ways to explore the range of possible solutions. The simplest question to ask is that of the allowed range of one or more of the components of the budget. However the formalism also provides the capability for exploring the allowed range of joint variability of a set of two or more variables. We produce what we call 'mutual-consistency-regions' (MCRs) which we define to be the set of contributions consistent with all the constraints. For N components, the MCR will be an N-dimensional polyhedron. We also consider the range of consistency of subsets of variables. The MCR of such a set of M components will be the projection of the N-dimensional region onto the M-dimensional space of components considered.

3b. The mathematical formalism

The mathematical expression of the linear programming problem is defined in terms of a set of N variables, x_j for $j = 1$ to N. In the present study these correspond to INCRES, FOSSIL etc. (The actual ordering of the variables is generally irrelevant and for the programs used here is taken from the input file defining the code names.) The x_j are required to be inherently positive. The constraints $x_j \geq 0$ are implicit in the linear programming formalism and need not be entered explicitly. Any quantity that can be of either sign must be re-expressed in terms of possible positive and negative contributions:

$$\text{Y} = \text{Y\_POS} - \text{Y\_NEG}$$

with Y_POS and Y_NEG assigned to different x_j. This issue can become important when considering detailed regional carbon budgets.

The variables x_k are regarded as being subject to various linear constraints:

$$\sum_k a_{jk} x_k \leq e_j$$

$$\sum_k b_{jk} x_k \geq f_j$$

$$\sum_k c_{jk} x_k = g_j$$

The linear programming problem is to find the maximum (or minimum) of some linear combination of the x_j, i.e. a sum such as $\Psi = \sum_j \psi_j x_j$.

Implementations of algorithms for solving this linear programming problem can differ in various sign conventions adopted. The first choice is whether a particular procedure maximises or minimises Ψ. Changing the sign of all the ψ_j converts a maximisation problem into a minimisation problem without loss of generality. A second choice is usually made to force all the inequalities into a standard form. Inequalities $\leq$ and $\geq$ are reversed by reversing the signs of all coefficients. This can be used either to make all the inequalities of the one direction *or* all the right-hand sides of one sign.

In applying the linear programming formalism to studying the atmospheric carbon budget, the first thing that can be done is simply to look at the extreme values of each of the components. This, is simply a matter of setting $\psi_j = \pm 1$ for one particular j value, with all other ψ_j zero. Greater insight into the range of uncertainty in the atmospheric carbon budget can be obtained by looking at the jointly allowed values of two distinct components. This can be done by maximising $a_j x_j + a_k x_k$ for the desired choices of j and k for a range of a_j, a_k defining different directions in the x_j-x_k plane. Appropriate choices of a_j and a_k will determine the vertices of the polygonal bound of the MCR in the x_j-x_k plane and this region can then be plotted. Similarly more complex combinations can be explored but the results are harder to represent visually. In order to explore the joint variability of 3 quantities x_j, x_k and x_m we choose a set of allowed values of x_m and determine cross-sections of the 3-variable MCR for various fixed x_m by calculating 2-variable MCRs with the additional constraint of fixed x_m.

3c. The combined uncertainties

In order to illustrate the formalism described above, we apply it to the simplest case of a global description of the atmospheric carbon budget, using the constraints developed in Section 2 above.

As outlined in the introduction we present estimated atmospheric carbon budgets at two distinct times, 1978 and 1988, recognising that these refer to running averages around these times rather than budgets for the single years. In addition we consider the period 1980–1985, subject to the caveats concerning the apparently anomalous behaviour of the cycle.

Table 2 displays the constraints described in Section 2 above with '78', '88' and '83' representing three alternative sets of 'right-hand-sides' applying for 1978, 1988 and 1980–5 respectively.

INCRES	FOSSIL	OCEANS	CLEARS	FERTIL	.	'78'	'88'	'83'
-1.0	1.0	-1.0	1.0	-1.0	$=$	0.0	0.0	0.0
1.0	0.0	0.0	0.0	0.0	$\geq$	2.98	3.32	2.98
1.0	0.0	0.0	0.0	0.0	$\leq$	3.38	4.16	3.18
0.0	1.0	0.0	0.0	0.0	$\geq$	4.88	5.57	4.94
0.0	1.0	0.0	0.0	0.0	$\leq$	5.65	6.45	5.72
0.0	0.0	1.0	0.0	0.0	$\geq$	0.80	0.98	0.89
0.0	0.0	1.0	0.0	0.0	$\leq$	2.64	3.32	2.93
0.0	0.0	0.0	1.0	0.0	$\geq$	0.79	1.28	0.96
0.0	0.0	0.0	1.0	0.0	$\leq$	2.10	3.32	2.56
0.0	0.0	0.0	0.0	1.0	$\geq$	0.60	0.80	0.70
0.0	0.0	0.0	0.0	1.0	$\leq$	1.80	2.40	2.10

Table 2: Constraints based on direct estimates of components of the atmospheric carbon budget. Units are Gt C y^{-1}. Each line in the body of the table represents a distinct constraint for each of the 3 times considered.

It is found that combining the information does not reduce the initial range of uncertainty for any of the variables in any of the cases. This was to be expected since there is only one constraint (a balanced atmospheric budget) linking variables that are otherwise independent. The effects of the constraint become apparent in the plots of the mutual consistency regions (MCRs) of various sets of variables. Figure 1 shows the allowed joint variation of OCEANS and CLEARS. It shows that the combination of low oceanic uptake and high rates of clearing cannot both occur together. Figure 2 shows the allowed joint variation of OCEANS and FERTIL. In this case the combination of low oceanic uptake and low fertilisation uptake are seen to be excluded.

It is Figure 3 that gives a better idea of the inter-relation of the constraints. It is based on a modification of the standard case. The fossil fuel range is reduced to (-2.5% to $+5$%). Figure 3 shows the combined ranges of CLEARS and FERTIL for various fixed values of OCEANS, i.e. the figure shows cross-sections if the 3-variable MCR for OCEANS, CLEARS and FERTIL. From the figure it becomes clear that for any fixed value of oceanic uptake, the net biotic source (CLEARS $-$ FERTIL) is constrained. The allowed values of CLEARS and FERTIL form a diagonal band. The length of the band is set by the prior constraints on the two quantities. The width of the band (as measured parallel to either axis) is the sum of the ranges of INCRES and FOSSIL.

Finally, in Figure 4 we show the effect on the MCRs of the secular change in the global carbon system. The figure shows the 2 MCRs for the '1978' and '1988' cases. Comparisons with the corresponding region for the 1980–1985 case shown in Figure 1 shows an increase in the absolute range of uncertainty over time. For most components, the uncertainty grows with the size of the source or sink. The displacement between the two regions shown in Figure 4 is a small but significant part of the allowed range of variability, even with the large uncertainties that remain in budgets based solely on direct estimates. When additional information is supplied to reduce these ranges, the secular changes can become comparable to the range of uncertainty.

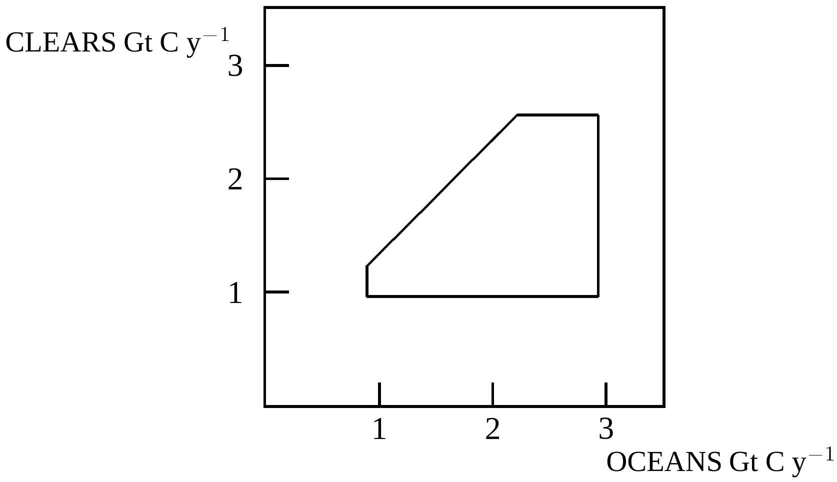

Figure 1: Joint variation of OCEANS and CLEARS given the constraints from Table 2 for the 1980–5 case. The region within the polygon corresponds to the set of mutually consistent values for the net oceanic uptake and the net rate of carbon release from land-use changes.

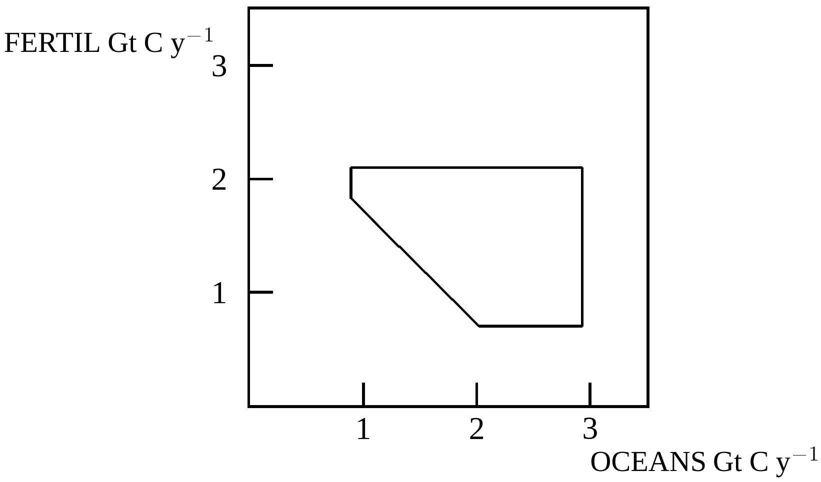

Figure 2: Joint variation of OCEANS and FERTIL given the constraints from Table 2 for the 1980–5 case.

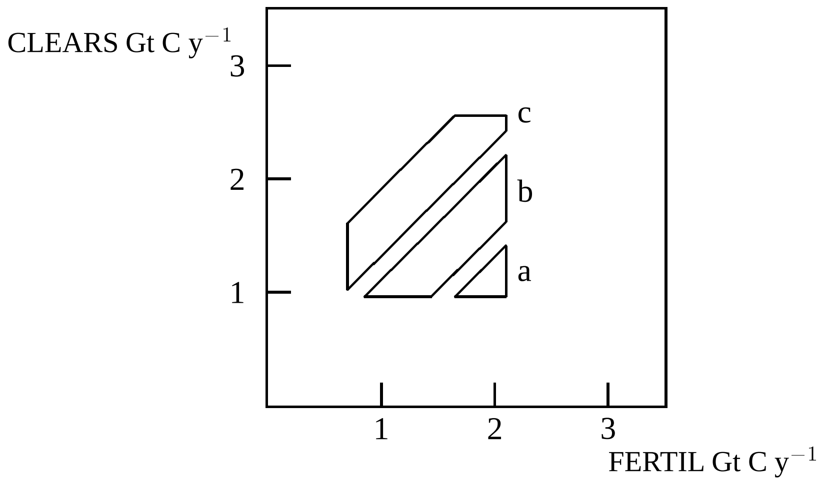

Figure 3: Joint variation of FERTIL and CLEARS for various fixed values of OCEANS: (a) 1.2 Gt C y^{-1}, (b) 2.0 Gt C y^{-1} and (c) 2.8 Gt C y^{-1}, given the constraints from Table 2 for the 1980–5 case except that the range of fossil fuel release is taken as 5.07 to 5.46 Gt C y^{-1}. The three polygons are cross sections of the 3-dimensional region of allowed variability of OCEANS, CLEARS and FERTIL.

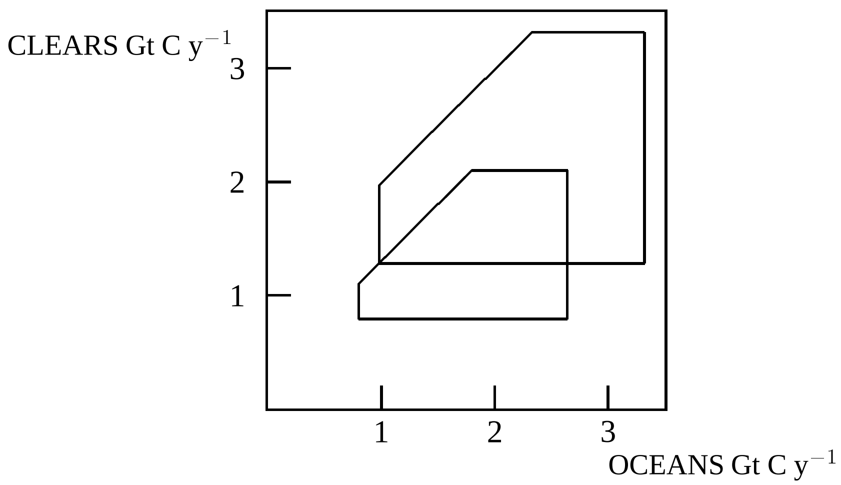

Figure 4: Joint variation of OCEANS and CLEARS given the constraints from Table 2 for the 1978 and 1988 cases (lower left and upper right polygons respectively).

4. Model-based Constraints on Oceanic Uptake

4a. General

As an alternative to the use of direct information about the oceanic uptake of CO_2 we can follow the 'traditional' approach from carbon cycle modelling and calculate the oceanic CO_2 uptake using a model. Even in the context of a 'perfect' model, the present oceanic uptake of CO_2 will depend on the history of past changes. The relationship can be conveniently expressed using the response function formalism introduced by Oeschger and Heimann (1983).

Given the assumption of stationarity, a linear treatment gives the relation between the net terrestrial source, $S(t)$, and the concentration, $C(t)$, as:

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

where $R(t)$ is a response function that gives the amount of CO_2 remaining in the atmosphere at a time t after a unit input. This relation has a formal inverse:

$$S(t) = \dot{Q}(t)/R(0) - Q(t)\dot{R}(0)/R(0)^2 - \int_{t_0}^{t} K(t-t')\,Q(t')\,dt' \tag{4}$$

The inversion kernel $K(.)$ is related to $R(.)$ (Enting and Mansbridge, 1987b). If R is approximated as a sum of N exponentials then K can be readily derived as a sum of $N-1$ exponentials. The oceanic uptake $\Phi(t)$ can be written as:

$$\Phi(t) = S(t) - \dot{C}(t)/R(0) = -Q(t)\dot{R}(0)/R(0)^2 - \int_{t_0}^{t} K(t-t')\,Q(t')\,dt' \tag{5}$$

This relation shows that the oceanic uptake for a particular time t is expressed in terms of the history of concentration change without having to make explicit reference to the history of sources that produced that change.

With the availability of measurements of past CO_2 concentrations from bubbles in polar ice (e.g. Neftel, 1985) it has been possible to determine the current oceanic carbon uptake by either:

- Using a full carbon cycle model with the atmospheric concentration constrained to follow the ice-core record;
- Using the response function representation of such a model with the atmospheric concentration constrained to follow the ice-core record;
- Using the inversion relation above with the kernel $K(.)$ derived from the model response function.

The two terms in the expression for Φ have opposite signs (K positive and $\dot{R}(0)$ negative) and so in principle Φ could show variations more rapid than $C(t)$. However the effect of steadily increasing $C(t)$ will be steadily increasing oceanic uptake, Φ. To quantify this we use the results of the modelling study reported by Enting (1991) (which formed the basis of some of the calculations reported in the IPCC report). The oceanic uptake in this modified version of the box-diffusion model (with the parameters taken from Broecker et al., 1980) was 1.6 Gt C y^{-1} for 1978, 2.0 Gt C y^{-1} for 1988 and 1.8 Gt C y^{-1} averaged over 1980–1985. For the purposes of the present analysis we use factors of -10% and $+10$% to rescale direct estimates for 1980–1985 to be applicable to 1978 and 1988 respectively.

In spite of the wide variety of models, several important common features occur, distinguishing modelling from direct estimation of CO_2 uptake. Firstly, p_{CO2} is calculated from the model equations rather than relying on the limited observational data. Secondly, the oceanic uptake over long periods is only weakly dependent on the air-sea gas exchange coefficient E. Finally, correction terms such as the skin effect and river carbon have their main influence on the steady-state distribution of carbon between atmosphere and ocean and have only minor second-order effects on the response to perturbations in atmospheric CO_2. Thus the main causes of uncertainty in direct estimates (see Section 2c above) are largely bypassed by ocean modelling, but the results are conditional on the validity of the model that is used.

4b. Non-stationarity

The formalism outlined in the previous section applies to general linear stationary models. The question of linearity is not a serious issue. The main non-linearity in oceanic uptake involves the relation between carbon content and p_{CO2} in the ocean mixed layer. However in describing the response to additional carbon inputs, this non-linearity only becomes significant at concentrations much greater than those occuring at present.

A more important question is whether the ocean transport processes have remained unchanged in time. A related question is whether the pre-industrial distribution of CO_2 in the atmosphere and oceans represented an equilibrium consistent with present oceanic transport of whether the pre-industrial distribution reflected a different transport regime in the past.

On the time scale of 2 to 4 years the El Niño/Southern Oscillation (ENSO) phenomenon represents a non-stationary influence on atmospheric CO_2.

One piece of evidence for a longer-scale non-stationarity within the industrial period is the study by Enting and Mansbridge (1987) and the refined analysis by Enting (1992). The result of these studies is that there is no response function for a linear steady-state ocean that can reconcile the CO_2 record from ice-cores with the release estimate obtained by summing the fossil carbon estimates from Rotty and the biotic sources estimated by Houghton et al. (1983). The study by Enting (1992) shows that including a fertilisation effect in the calculation increases the discrepancy. The solution proposed by Enting (1992) was that the ice-core record for the early part of the industrial period included an oceanic component reflecting some non-stationary behaviour, possibly a recovery from a perturbation associated with the little ice age.

The possibility of non-stationarity in the ocean mixing processes remains as a caveat to all current use of ocean models for either interpreting the atmospheric carbon budget or for predicting future CO_2 levels.

4c. Parameterised Models

Most carbon cycle modelling has made use of highly parameterised representations of the ocean. Perhaps the most widely used of such models is the 'box-diffusion model' introduced by Oeschger et al. (1975) and used (with a variety of refinements) in many subsequent studies.

Because of the 'lumped' structure of such models, the ocean mixing parameters have little direct relation to observable physical transport and so the model mixing has to be determined by calibrating the model using observed tracer distributions. Most commonly ^{14}C is used for such calibration.

In many modelling studies, sensitivity studies have been carried out, investigating the extent to which model results are sensitive to variations in the model parameters. However, given the way that the models are calibrated, the most relevant question is the extent to which the model results depend on those parameter variations (and combinations of variations) that are consistent with the calibration data.

There have been two studies that addressed this more complicated question. Gardner and Trabalka (1985) used a 'Monte Carlo' approach, generating a large sample of pseudo-random sets of parameter variation and analysed the properties of the sub-sample that was consistent with various carbon cycle data. Enting and Pearman (1986, 1987) used numerically determined derivatives to search for the directions in parameter space having the most extreme sensitivity consistent with the calibration data. This was done within the context of a 'Bayesian' calibration that fitted both the carbon cycle data and independent estimates of the model parameters.

Recently this approach has been used on a modified version of the box-diffusion model to explore the range of possible uptakes consistent with carbon cycle data. This study was in terms of a restricted set of changable parameters, chosen to reflect those which the preliminary analytic study by Enting (1990) had suggested as most critical in determining the range of oceanic uptake consistent with the data. In particular the model was used to explore the possible role of detrital transport in removing ^{14}C from the ocean surface so that the observed uptake of ^{14}C from nuclear tests could be reconciled with low oceanic uptake of CO_2.

The Bayesian calibration adjusted 6 model parameters, 2 for detrital transport (organic and carbonate detritus having different depths of re-dissolution), the eddy mixing in the ocean, the atmospheric turnover time with respect to ocean uptake, and the two parameters for ^{14}C production (from cosmic rays and nuclear tests). The model was run in inverse mode, tracking the CO_2 record from ice cores. The model output (primarily isotopic information since atmospheric CO_2 changes were fitted exactly) was fitted to a set of 15 data items similar to that used by Enting and Pearman (1987) without the spatial disaggregation.

The range of oceanic uptake was explored by using the Lagrange multiplier formalism described by Enting (1985) and applied by Enting and Pearman (1986, 1987). It was found that a range of about ± 0.33 Gt C y^{-1} of biotic exchange approximately doubled the sum of squares of residuals relative to the best fit. For 15 independent variables (given 6 variables fitted to 15 + 6 quantities) a doubling corresponds to a χ^2 of 30 and thus a 'confidence' value of 99%. The range of ± 0.33 Gt C y^{-1} was adopted for the analyses presented below.

4d. Direct inversion

A somewhat different approach to the calibration of lumped models of ocean circulation seeks to obtain transport coefficients more closely linked to actual water-mass movements by inverting the distribution of a suite of chemical tracers. This approach was attempted by Bolin et al. (1983) who used carbon, oxygen, alkalinity, phosphorus and ^{14}C to determine the transport coefficients (and biological contributions) for a 12-box representation of the global ocean.

The inversion calibration of the 12-box model leads to significant discrepancies between observed and calculated distributions of phosphorus. The CO_2 uptake calculated by the model using fossil fuel inputs corresponded to an airborne fraction of 70%. The relevance of this calculation is limited by the neglect of biotic inputs, probably implying too low a value for atmospheric CO_2, and the fact that the very large uptake also led to lower than observed CO_2, thus giving an underestimate of Φ. A more satisfactory approach, avoiding both these problems would be to run the model with the atmospheric CO_2 concentration history specified by the record from ice-cores.

The authors regarded the model results as limited by the resolution. Later work by the same group has used much greater resolution but has concentrated on the Atlantic Ocean (see for example Moore and Björkström, 1986).

4e. Ocean general circulation models

The use of ocean general circulation models that derive the ocean transport from a knowledge of the basic physics would be one way of removing much of the uncertainty in the oceanic uptake of CO_2. At present there are two main limitations on doing this:

- The models require considerable computing resources, particularly given that characteristic scales of oceanic eddies are much smaller than for atmospheric eddies.
- The development of ocean GCMs is still continuing; in existing GCMs a number of parameterisations are required in order to produce acceptable circulation patterns.

In spite of these difficulties, there have been several calculations of oceanic CO_2 uptake using models based on the transport calculated by a GCM (Maier-Reimer and Hasslemann, 1987;

Bacastow and Maier-Reimer, 1990; Sarmiento, 1986; see also Sarmiento and Sundquist, 1992).

For the purposes of the present study, the various estimates suffer from a lack of comparability in time and a lack of any estimate of uncertainty apart from the obvious model-to-model differences. Maier-Reimer and Hasselmann (1987) quote an oceanic uptake of 40% of fossil releases (i.e. 2.05 Gt C y^{-1} for 1978) while Bacastow and Maier-Reimer quote a fraction of 32% (i.e. 1.64 Gt C y^{-1} for 1978). Sarmiento and Sundquist (1992) quote results of 1.9 Gt C y^{-1} uptake for the period 1980–1989 and an average of 1.7 Gt C y^{-1} for 1972–1989.

The most satisfactory way of achieving comparibility of time periods would be to take the response function $R(t)$ for each model and derive the oceanic uptake by applying relation (5) to the CO_2 record from ice-cores. This requires a knowledge of the response function for each model. For example Maier-Reimer and Hasselmann (1987) represent the CO_2 uptake in their ocean model by

$$R(t) = 0.131 + 0.201\exp(\tfrac{-t}{362.9}) + 0.321\exp(\tfrac{-t}{73.6}) + 0.249\exp(\tfrac{-t}{17.3}) + 0.098\exp(\tfrac{-t}{1.9})$$

Given a response function $R(t)$ and a specification of atmospheric CO_2 changes $C(t)$, the oceanic uptake can be calculated for any time t. Thus a specfication of $R(t)$ greatly simplifies comparisons between models.

4f. Use of constraints on ocean uptake

The inclusion of model-based estimates of the global oceanic uptake of CO_2 does not change the structure of the analysis presented in Section 3c above. All that happens is that the rather broad band of direct estimates is replaced by a somewhat narrower range. Given the range of approaches to ocean carbon modelling there is no 'one-true-range' to be quoted on the basis of current knowledge. It is simply a matter that the more that is assumed about the validity of a model, the tighter the range that can be obtained, conditional on the validity of the assumptions made.

In presenting the analysis of model-based constraints, we use

$$1.47 \leq \text{OCEANS} \leq 2.13 \tag{6}$$

based on the Bayesian calibration of the box-diffusion model. This applies to 1980–1985; shifts of -0.2 and $+0.2$ give the 1978 and 1988 values.

This reduction in the range relative to the prior estimates is not sufficient to reduce the possible range of any of the other quantities to less than their respective prior ranges, apart from a minor reduction in the upper bound on CLEARS from 2.56 to 2.47 Gt C y^{-1}. Figure 5 shows the allowed joint range of CLEARS and FERTIL. Compared to the examples in section 3, excluding the upper range of oceanic uptake has precluded combinations of high deforestation and small amounts of fertilisation.

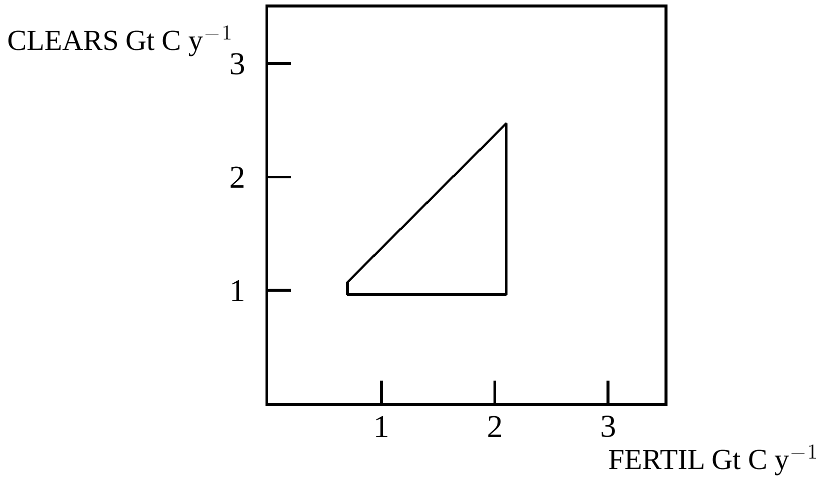

Figure 5: Joint variation of FERTIL and CLEARS, given the constraints from Table 2 for the 1980–5 case but with the range of oceanic uptake determined by Bayesian calibration of the box-diffusion model.

This results must be considered as an illustrative example, being subject to the validity of a highly simplfied model. While improvements in ocean GCM models can be expected to increase the confidence in their results, for the present all attempts to use ocean modelling to constrain the atmospheric carbon budget must be regarded as model-dependent.

5. The Role of Regional Constraints

5a. General

Over the last few decades, the spatial coverage of CO_2-observing networks has increased considerably. The aim of these programs is to use the spatial distribution of CO_2 concentrations to deduce the spatial distribution of sources and sinks, thus constraining the possible processes. The determination of source strengths from concentration data requires the use of an atmospheric transport model.

The use of spatially disaggregated budgets is limited by the problem raised in the previous section — that of error bounds for the model calculations. None of the initial deconvolutions (Enting and Mansbridge, 1989; Tans et al., 1989; Enting and Mansbridge, 1991) included any sort of estimated range of uncertainty.

As an example of how regional constraints can be used, we consider a simple 3-region division into ‘north’, ‘south’ and ‘tropical’. For comparison with earlier work, we use the division considered by Enting and Mansbridge (1991), taking the 'tropical' region as being between 12°S and 12°N. The results of a source deduction using a transport model will be in the form of regional sources which we denote T_RELS, N_RELS and S_SINK. The various surface source processes have to be similarly divided into components that give the correct total so that:

- OCEANS = N_SEAS + S_SEAS − T_SEAS
- FOSSIL = N_FOSS + S_FOSS + T_FOSS
- CLEARS = N_CLER + S_CLER + T_CLER
- FERTIL = N_FERT + S_FERT +T_FERT

(It is assumed that all the processes have regional fluxes in the same sense as the total, except for the oceans which are assumed to be a net source in the 'tropical' region and net sinks at higher latitudes.)

The regional source balances are:

- N_RELS = N_FOSS + N_CLER − N_SEAS − N_FERT
- T_RELS = T_FOSS + T_CLER + T_SEAS − T_FERT
- S_SINK = − S_FOSS − S_CLER + S_SEAS + S_FERT

What is needed to complete this analysis is error bounds for the regional source components. A significant complication is that these error ranges will *not* be independent. One constraint that reduces the independence of the regional source components will be the relation:

- INCRES = N_RELS + T_RELS − S_SINK

The effect of this constraint could be included by including the equality into the linear programming formalism; it will imply upper and lower bounds on the (algebraic) sum of regional sources, arising from the range of increases compatible with the data. However such constraints should arise directly as part of the error analysis that considers the range of regional source components that are consistent with the data. Unless the error analysis of the source deduction can produce such constraints (or subsume them under stronger constraints) it can not be regarded as adequate. This question is further addresssed in Section 5c below.

5b. Constraints from direct estimates

In most cases the direct estimates presented in Section 2 were obtained as sums over regional contributions and so there is no difficulty, in principle, in obtaining corresponding regional estimates, although in some cases the relevant data may be less accessible than the global totals.

Fossil For fossil carbon release, we use the distribution given by Enting and Mansbridge (1991) with 3.8%, 3.5% and 92.7% of emissions from the 'south' 'tropical' and 'north' regions respectively. The range of uncertainty is again taken and -5% to $+10$%. As noted for illustrative purposes below, the regional estimates will contain uncertainties not present in the global totals, arising from effects such as fuel use in transport. However, these effects will be relatively small and are neglected in the present analysis.

Oceans The direct estimates are taken from the work of Tans et al. (1990), modified by the correction terms from Sarmiento and Sundquist (1992) as described in Section 2. Since one third to one half of the uncertainty comes from uncertainty in the gas exchange formalism, assuming a consistent treatment gives a constraint on the global total that is tighter than the combination of the individual regional ranges.

Clearing As discussed in Section 2d above, Houghton et al. (1987) give a detailed description of the spatial distribution of net CO_2 emissions resulting from land-use changes.

Fertilisation The estimates from Kohlmaier et al. (1987) as quoted in section 2e above are converted to regional estimates by (i) taking their estimates for the living component of extra uptake in tropical forests (ii) using the Polglase model to suggest a very small contribution from litter and soil in tropical forests (iii) using the zonal estimates of NPP assembled by Pearman and Hyson (1986) to give a 2:1 ratio of NPP in our northern and southern regions.

On the basis of this information we take the living component as having the range 0.14 to 0.43 Gt C y^{-1} in the north, 0.16 to 0.36 Gt C y^{-1} in the tropics and 0.08 to 0.21 Gt C y^{-1} in the south. The non-living component is assigned the ranges 0.2 to 0.6, 0.0 to 0.2 and 0.1 to 0.3 (all Gt C y^{-1}) for north, tropics and south respectively.

5c. Constraints from atmospheric modelling

Modelling of the spatial distribution of atmospheric CO_2 can be performed in two main ways known as forward modelling and inverse modelling. In forward modelling, surface fluxes are modelled and an atmospheric transport model is used to calculate the resulting CO_2 concentrations. The fluxes can be adjusted to bring the calculated concentrations into better agreement with observations. In inverse modelling, the model is run with the surface concentrations forced to follow a specified concentration field. The surface sources are then calculated by mass balance. Examples of forward modelling studies of the spatial distribution are Pearman and Hyson, 1980, 1986; Fung et al., 1983; Pearman et al., 1983; Keeling et al., 1989b; Tans et al., 1990). Examples of inverse modelling are Enting and Mansbridge, 1989, 1991; Tans et al., 1989).

As noted above, there has been relatively little attention paid to the question of error estimates for sources derived from atmospheric transport modelling. In order to explore the extent to which such modelling can reduce uncertainties in the atmospheric carbon budget we present some preliminary analyses based on a purely diffusive representation of atmospheric transport. Such modelling has been used to explore the degree of ill-conditioning in the problem of deducing source-strengths from atmospheric concentration data (Newsam and Enting, 1988; Enting and Newsam, 1990).

The analysis considers the question of the surface source strength of CO_2, integrated over various latitude bands. It is based on fitting observed annual mean CO_2 concentrations (as a weighted sum of Legendre polynomials), deducing the source strength implied by the concentrations and then adjusting the concentration fit so as to determine the maximum and minimum of the latitudinally integrated source, subject to the concentration curve having a specified level of agreement with the data.

There is, as yet, no good statistical basis on which to deduce error ranges for this problem. A preliminary discussion is given by Enting and Pearman (1992) where it is emphasised that it is vital to characterise the 'noise' processes that influence the observational data.

The ranges used in the present example are based on fitting 19 annual mean concentrations as given by Tans et al. (1990). (The data from Shemya and the Azores were omitted because they appeared too anomalous to be fitted with a zonally-averaged representation.). The remaining data points were fitted using Legendre polynomials up to $k = 11$ with the requirement that the fit agree with each data item to within 0.4 ppmv. An additional smoothness constraint was applied, bounding the magnitude of the coefficients of the Legendre polynomials P_k by $10/k$. The trend was taken as 1.45 $\pm$ 0.05 ppmy y^{-1}. This led to the ranges (-1.96 to -0.51), (0.09 to 1.28) and (3.24 to 3.89) for southern, tropical and northern regions respectively. Changing the order of the fit to $k = 10$ reduced the southern range to -1.87 to -0.63); reducing k to 9 made it impossible to fit the data to the required precision.

As noted above, these various ranges are not independent. However the constraints on the sums of pairs of sources is essentially given by combining the constraint on the third regional component with the requirement that the total match the atmospheric increase. Other aspects of the covariance remain to be explored.

5d. Combining regional constraints

As noted above, the example that we present here follows Enting and Mansbridge (1991) in considering a 'tropical' region of 12°S to 12°N. The additional working variables that we use are N_RELS, N_FOSS, N_CLER, N_SEAS, N_FERT, T_RELS, T_FOSS, T_CLER, T_SEAS, T_FERT, S_SINK, S_FOSS, S_CLER, S_SEAS, S_FERT and INCRES. The equalities expressing the global variables OCEANS, FOSSIL, CLEARS and FERTIL as sums of their regional contributions could be used to remove these variables from the calculation, but it is convenient to retain them in the calculation in order to explore their possible ranges. Very few of the direct estimates will be more precise on a global scale than would be implied by the combination of regional constraints. In cases where a more precise global constraint is available (e.g. for fossil fuel where transport use gives a regional uncertainty that is absent from the global totals) it would still be possible to avoid using a variable for the global total by expressing the more precise global bound in terms of the sum of regional contributions.

The regional budget is only analysed for the period 1980–1985 because of the lack of well-intercalibrated data from earlier periods and the fact that much of the more recent observations are either unpublished or else only published in provisional form. The constraints based on direct estimates are:

$$2.98 \leq \text{INCRES} \leq 3.18 \tag{7}$$

$$0.19 \leq \text{S\_FOSS} \leq 0.22 \tag{8a}$$

$$0.17 \leq \text{T\_FOSS} \leq 0.20 \tag{8b}$$

$$4.58 \leq \text{N\_FOSS} \leq 5.30 \tag{8c}$$

$$0.01 \leq \text{S\_CLER} \leq 0.04 \tag{9a}$$

$$0.90 \leq \text{T\_CLER} \leq 2.36 \tag{9b}$$

$$0.05 \leq \text{N\_CLER} \leq 0.16 \tag{9c}$$

$$0.18 \leq \text{S\_FERT} \leq 0.51 \tag{10a}$$

$$0.16 \leq \text{T\_FERT} \leq 0.56 \tag{10b}$$

$$0.36 \leq \text{N\_FERT} \leq 1.03 \tag{10c}$$

$$1.15 \leq \text{S\_SEAS} \leq 2.78 \tag{11a}$$

$$0.51 \leq \text{T\_SEAS} \leq 1.08 \tag{11b}$$

$$0.48 \leq \text{N\_SEAS} \leq 1.50 \tag{11c}$$

with a constraint on the total oceanic uptake of:

$$0.89 \leq \text{S\_SEAS} - \text{T\_SEAS} + \text{N\_SEAS} \leq 2.93 \tag{12}$$

The constraints based on atmospheric transport are provisionally set at

$$0.51 \leq \text{S\_SINK} \leq 1.96 \tag{13a}$$

$$0.09 \leq \text{T\_RELS} \leq 1.28 \tag{13b}$$

$$3.24 \leq \text{N\_RELS} \leq 3.89 \tag{13c}$$

The equalities defining relations between the components are:

$$\text{N\_RELS} = \text{N\_FOSS} + \text{N\_CLER} - \text{N\_SEAS} - \text{N\_FERT} \tag{14a}$$

$$\text{T\_RELS} = \text{T\_FOSS} + \text{T\_CLER} + \text{T\_SEAS} - \text{T\_FERT} \tag{14b}$$

$$\text{S\_SINK} = -\text{S\_FOSS} - \text{S\_CLER} + \text{S\_SEAS} + \text{N\_FERT} \tag{14c}$$

$$\text{INCRES} = \text{N\_RELS} + \text{T\_RELS} - \text{S\_SINK} \tag{15}$$

The linear programming analysis was applied to these constraints (48 constraints on 20 variables). Many of the quantities were not constrained beyond the constraints listed above. Cases in which the derived constraints differed from the initial direct estimates were:

$$\text{FERTIL} > 0.84 \qquad \text{c.f. 0.70 prior limit} \tag{16a}$$

$$\text{CLEARS} < 1.36 \qquad \text{c.f. 2.56 prior limit} \tag{16b}$$

$$\text{T\_SEAS} < 0.77 \qquad \text{c.f. 1.08 prior limit} \tag{16c}$$

$$\text{S\_SEAS} < 2.04 \qquad \text{c.f. 2.78 prior limit} \tag{16d}$$

$$\text{T\_CLER} < 1.16 \qquad \text{c.f. 2.36 prior limit} \tag{16e}$$

$$\text{T\_RELS} > 1.02 \qquad \text{c.f. 0.09 prior limit} \tag{16f}$$

$$\text{S\_SINK} > 1.08 \qquad \text{c.f. 0.51 prior limit} \tag{16g}$$

The reduction in total clearing reflects the constraint on the tropical component. Figure 6 illustrates this. In contrast, the reduction in the southern ocean sink has not had a corresponding effect on the ocean total. This reflects the fact that the oceanic estimates are correlated by virtue of their dependence on the gas-exchange formalism. This was taken into account in producing the global total but is not otherwise reflected in the constraints given above. However Figure 7 shows that any further constraint on the southern ocean sink would constrain the global total.

Because of the approximate nature of the transport relation used to derive the sources, it is inappropriate to assign great significance to the particular numbers. The important point to note is that even though the uncertainties in source estimates from transport modelling may be quite large, such information can still give useful constraints on the atmospheric carbon budget.

6. Concluding remarks

The preceding sections have described the linear programming formalism for analysing atmospheric carbon budgets and have presented some preliminary examples of the application of this approach. The analyses have been presented at three levels of detail, chosen (somewhat arbitrarily) as being based on:

- Direct estimates of the source components.
- Direct estimates supplemented by global modelling of oceanic uptake.
- Combinations of regional budgets, related using atmospheric transport modelling.

These studies have revealed some of the key weaknesses in our current knowledge.

In order to reduce the uncertainties in the atmospheric carbon budget there are two approaches (by no means mutually exclusive). The first is to improve the precision of the estimates used. The second is to incorporate new types of information.

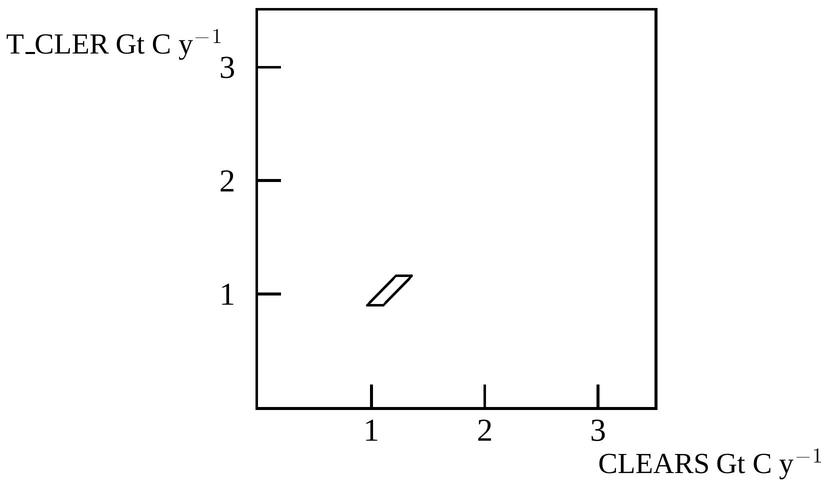

Figure 6: Joint variation of CLEARS and T_CLER, given the constraints from Table 2 for the 1980–5 case and the regional constraints listed in equations (7) to (15).

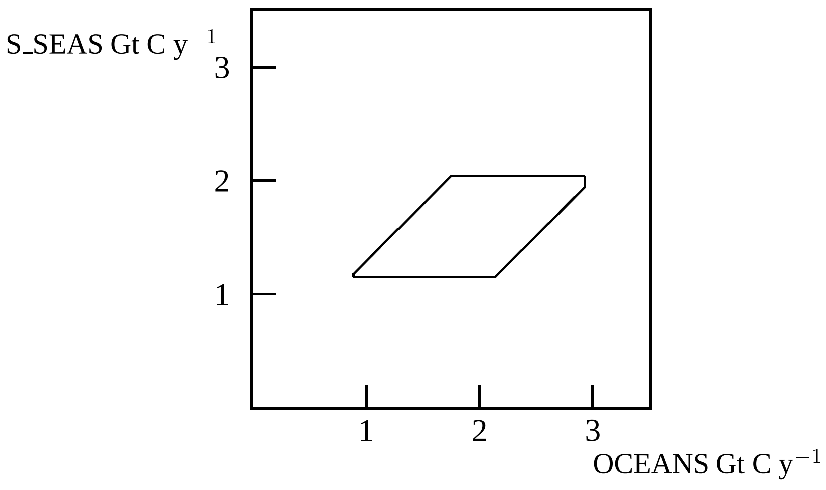

Figure 7: Joint variation of total ocean sink, OCEANS, and southern oceans sink, S_SEAS, given the constraints from Table 2 for the 1980–5 case and the regional constraints listed in equations (7) to (15).

The areas in which there may be scope for improvement are:

- Regional source budgets from atmospheric transport modelling. The construction of error estimates is a difficult problem but one that is being addressed. One of the motivations for the preliminary analysis presented in Section 5 was to explore the requirements for incorporating regional information into overall atmospheric budgets. The results show that even though the ill-conditioned nature of the source deduction problem leads to large uncertainties in regional source distributions, such regional information can still give useful constraints on the global budget.
- The area in which improvements in the direct estimates is most desirable is in the 'fertilisation' contribution. Present estimates a based on extrapolation of laboratory-determined β values to the global scale. Although a number of model calculations have been made, they are subject to very considerable uncertainty and there seems to be little hope of refining the precision to the extent that would give independent constraints on the atmospheric carbon budget.
- There would seem to be a strong possibility that uncertainties in direct estimates of air-sea fluxes will be reduced, at least by the extent implied by uncertainties in the gas-exchange coefficient. Direct flux measurements should be able to distinguish between the two forms and hopefully lead to an understanding of how the discrepancy has arisen. This would provide a signifcant reduction in the uncertainties in direct estimates of oceanic CO_2 uptake. Further improvements could be obtained (with considerable effort) from more comprehensive sampling of p_{CO2}. However, the best hope for determining the oceanic CO_2 uptake may still lie with ocean GCMs.

Some of the additional types of information that could be incorporated into atmospheric carbon budgeting studies are:

- Data on ^{13}C distributions. In particular regional data should be able to distinguish oceanic from biotic contributions. Forward modelling of the ^{13}C distribution has been presented by Pearman and Hyson (1986) and Keeling et al. (1989b). What is needed is to quantify the uncertainties in such analyses in the same ways as is needed for CO_2.
- As noted above, ocean GCMs may be able to give additional information about the regional distribution of CO_2 uptake.

This report has a number of objectives:

- To present initial budget estimates to provide base cases against which to measure improvements in our knowledge;
- To guide modelling studies that seek to explore the range of uncertainty in the atmospheric carbon budget;
- To present a formalism that can be applied to other species such as methane.

Disclaimer

The budgets presented here are preliminary descriptions based on information available to the author. They are presented to illustrate two key points: the need for recognising the secular change when analysing atmospheric carbon budgets and the need to consider the error structure, particularly the error covariance when using regional budgets derived from atmospheric transport modelling.

These budgets are subject to several caveats:

- It has not always been possible to compare like with like in making some of the cross-comparisons. In particular the error bounds are taken from (or derived from) published sources. In some cases the use that is made above may imply a higher precision than the original authors intended. It is hoped that by describing the types of information required for carbon budgeting studies, this report will encourage the presentation of analyses of individual subsytems in a way that facilitates using the results in carbon budgeting studies.
- The linear programming technique used here gives a fitting procedure related to fitting under a ℓ_∞ norm. Such fitting is very sensitive to 'outliers' i.e. information that contains 'error' contributions inconsistent with the underlying system being analysed.
- The consistency regions determined from the regional budgets are purely illustrative, partly because the ranges in direct estimates were not always readily available but mainly because the techniques for producing the requisite information from atmospheric transport modelling are poorly developed. The analysis in Section 5 shows the type of error information that is required so that future transport modelling can address the needs of carbon budgeting studies.

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Address and contact details: CSIRO Atmospheric Research
Private Bag No.1 Aspendale Victoria 3195 Australia
Ph: (+61 3) 9239 4400; fax: (+61 3) 9239 4444
e-mail: chief@dar.csiro.au

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