2. Carbon Budget Issues

2a Budget issues

We write the atmospheric carbon budget (in units of Gt C y^{-1}) as:

$$2.123 \frac{d}{dt} C = Q_{\text{foss}}(t) + D_{\text{n}}(t) - S_{\text{ocean}}(t) - S_{\text{fert}}(t) - S_{\text{resid}}(t) \qquad (2.1)$$

where:
$C(t)$ is the atmospheric CO_2 concentration (in ppmv relative to dry air),
$Q_{\text{foss}}(t)$ is the 'fossil' emission rate, including both combustion of fossil fuel and CO_2 emissions from cement production. The IPCC (1990, 1992) reports used the term 'industrial' for this component,
$D_{\text{n}}(t)$ is the net carbon flux from land-use change (including delayed effects from past land-use changes),
$S_{\text{ocean}}(t)$ is the net carbon uptake by the oceans,
$S_{\text{fert}}(t)$ is the net flux associated with CO_2-enhanced growth,
$S_{\text{resid}}(t)$ is a residual-sink term, associated with climatic variability and any neglected processes.
The conversion factor, 2.123 GtC/ppmv, is the size of the atmosphere in moles, times the molecular weight of carbon, with the units of gram per unit ratio converted to GtC/ppmv.

There are a number of important points to note about the use of equation (2.1):

1. The budget equation (2.1) describes the perturbation about an assumed pre-industrial steady state. All the terms (except possibly $S_{\text{resid}}(t)$) refer either to anthropogenic forcing ($Q_{\text{foss}}(t)$ and $D_{\text{n}}(t)$) or to the natural response to such forcing ($\frac{d}{dt}C$, $S_{\text{ocean}}(t)$, $S_{\text{fert}}(t)$). These fluxes are net fluxes superimposed on large natural gross fluxes of carbon. In many cases the models will consider the gross fluxes, particularly when calculating isotopic effects. The distinction is well-understood within the field of carbon cycle modelling, but sometimes causes confusion when results are reported.

2. In practice we need to work with time averages of equation (2.1). At the very least we need to average over the seasonal cycle since these intra-annual changes are not included in this perturbation budget. We generally need to average over periods longer than a year in order to define a globally representative rate of change of CO_2. Multi-year averaging can also remove some of the short-term climatic variability that we have assigned to the term $S_{\text{resid}}(t)$.

3. The standard cases defined in the instructions assume that the residual 'missing-sink' term, $S_{\text{resid}}(t)$, is zero.

4. When using this equation in modelling, an initial pre-industrial state needs to be defined. In this connection, Enting (1992) has presented evidence that the fluctuation early in the industrial period shown by the ice-core data is too large to be due to the estimated anthropogenic sources.

2b Issues of definition

As noted in the Introduction, it is essential to ensure that the specifications of the carbon budget are both complete and consistent. Completeness is required both in the mathematical sense of being fully determined and in the physical sense of including all relevant carbon fluxes. However, such completeness must avoid both 'double-counting' of any fluxes and mathematical 'over-specification' which would generally imply inconsistencies in the description.

The process of mapping fluxes onto compartments with neither double-counting nor under-counting is complicated by the different levels of description that are adopted in different fields of study. In some cases, it is necessary to modify the model structure in order to match the definitions of the prescribed data.

Fossil/Industrial: This is intended to include all anthropogenic contributions to the net atmospheric carbon budget, except for those classified as associated with land-use change. In practice, the contributions are those from fossil fuel usage and cement production. The term 'industrial' (as used in IPCC, 1990, 1992) refers to the mode of production and not to the end-use. The term 'fossil' is taken to include cement production from fossil carbonate. This report uses 'industrial' and 'fossil' interchangeably. Estimates for years up to 1950 are based on the work of Keeling (1973) with later values from Rotty (1987) and Andres et al. (1994). The values are tabulated in Appendix A.

Fluxes from land-use change: This term is taken as being the **net** flux associated with present **and past** land use changes. This definition is chosen to match that used by the Woods Hole group (Houghton et al., 1983 and subsequent studies). It includes fluxes associated with deforestation (including decay of forest products), changes in soil carbon, changes associated with varying agricultural regimes, and forest regeneration on previously cleared land. The estimates for the past are from R.A. Houghton (personal communication) and are listed in Appendix A. For the future, we use a modified form of IS92a.

Oceans: This term is taken as the net transfer from the atmosphere to the oceans. There is believed to be a natural cycle in which carbon from the atmosphere is transferred to vegetation, transferred to the oceans via rivers and then returned to the atmosphere through outgassing (Sarmiento and Sundquist, 1992). This cycle can be ignored in the present global modelling. It becomes important when interpreting ocean CO_2 partial pressure data and (to a lesser extent) when interpreting inversions of spatial distributions of CO_2.

'Fertilisation': This needs to include all changes in terrestrial carbon that are not associated with land-use change. The key question for the projections presented here is the extent to which such fluxes can be reasonably assumed to grow with long-term increase in CO_2. ENSO-related effects generate short-term variations in the atmospheric carbon budget. A recent study by Dai and Fung (1993) indicates the possible importance of climatic variability on the decadal scale.

Anthropogenic: This is taken as the direct input of carbon to the atmosphere as a result of human activities. We regard this as the sum of the 'fossil' and 'land-use' components.

We explicitly exclude contributions that arise purely as a result of the increased CO_2 levels. In principle, anthropogenic emissions ought to include any changes in CO_2 fluxes associated with other man-made global change. However, in the present analysis any such fluxes would be included in the 'fertilisation' component in order to balance the budget.

It should also be noted that (2.1) represents an atmospheric carbon budget. Although a fraction of the carbon input enters the atmosphere as compounds other than CO_2, the vast majority of these are quickly oxidised to CO_2. For global averages, on time-scales of years, the atmospheric carbon budget is what determines the rate of increase of CO_2.

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