THE ROLE OF THE TERRESTRIAL BIOTA IN THE ATMOSPHERIC CARBON BUDGET:
Discussion notes for special session.

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1. INTRODUCTION

Throughout several decades of modelling of the global carbon cycle, the role of the terrestrial biota in the atmospheric carbon budget has been one of the greatest uncertainties.

There are three key questions:

- Most importantly: What will the atmospheric carbon budget be in the future?
- What is the atmospheric carbon budget now? Given the new uncertainties that have arisen about this, some resolution is needed before we can make confident predictions about the future.
- What has been the atmospheric carbon budget in the past? The history of past changes will place a number of constraints on the possible interpretations of the present atmospheric budget.

In this discussion, we will take 'the present' to refer to the period around 1980–1985 for which good quality atmospheric data have been published.

The most common units for discussing atmospheric carbon budgets are Gt C (gigatonnes of carbon). These are related to atmospheric concentration units by the factor 1 Gt C = 0.471 ppmv. The concentration increase of 1.5 ppmv y^{-1} observed over 1980–1985 thus corresponds to a rate of increase of atmospheric carbon of 3.185 Gt C y^{-1} . Rotty [1] estimated the fossil carbon releases for 1980 to 1984 as 5.255, 5.115, 5.082, 5.054 and

5.330 (provisional) Gt. Thus a sink of very close to 2 Gt C y^{-1} is required to balance the atmospheric carbon budget.

There have been three relatively distinct stages in the development of our interpretations of the atmospheric carbon budget:

- A period around 1980 in which global carbon cycle models seemed unable to account for enough uptake of CO_2 into the oceans. The discrepancy was small, around 0.5 Gt C y^{-1} if the terrestrial biota were regarded as being in a steady state. The study by Pearman [2] is typical of such work. The discrepancy was much greater if the terrestrial biota were regarded as a net source due to deforestation. Some of the earliest direct estimates of deforestation were produced around this time, with estimated releases of as much as 5–10 Gt C y^{-1} . Thus there was a search for a 'missing sink' in the atmospheric carbon budget.

- Later there was a realisation that conventional ocean mixing rates could account for large uptakes of CO_2 if they were responding to gradients established by large past releases. The mathematical relations were formalised by Oeschger and Heimann [3]. Enting and Pearman [4] produced a model whose present atmospheric carbon budget balanced because of the residual effects of proposed large carbon releases around 1900 — the so-called 'pioneer effect'. The same general form of release history was determined by Peng et al. [5] from the deconvolution of $\delta^{13}C$ in tree rings. (Comparison with $\delta^{13}C$ from ice-cores suggests that their tree-ring $\delta^{13}C$ record considerable overestimates the atmospheric change). The release histories had relatively small releases from the biota in recent decades — this was consistent with atmospheric transport modelling studies by Pearman et al. [6] who analysed the spatial distribution of CO_2 and found no evidence of the strong tropical CO_2 sources that would be expected from deforestation. The summation of this viewpoint is the determination by Siegenthaler and Oeschger [7] of the history of CO_2 releases over the last two centuries by performing a deconvolution of the history of CO_2 concentrations preserved in polar ice. We will refer to this as the conventional view.

- The recent work of Tans et al. [8] described in the next section suggests that the oceans are a much weaker sink (0.5–1.0 Gt C y^{-1}) and that the terrestrial biota are a strong sink. This was foreshadowed in part by two studies inverting CO_2 data [9], [10].

2. THE TANS ET AL. THESIS

Tans et al. [8] have suggested that the oceans are currently taking up only about 0.5 Gt C y^{-1} compared to the conventional estimates of around 2 to 3 Gt C y^{-1} . Their argument has 4 steps:

i Analysis of the north-south distribution of measured surface CO_2 concentrations suggests that the southern oceans are a relatively weak sink of CO_2 (in proportion to the ocean area) and that a major part of the CO_2 sink is in the northern hemisphere. This is supported by their studies using the three-dimensional tracer model of Fung et al. [11] and also by inversion studies using two-dimensional models to deduce zonally-averaged sources from concentration data [9], [10].

ii Direct measurements of p_{CO2} in northern and tropical oceans indicate that the northern oceans can not be a strong sink of CO_2 and that, as expected, the tropical oceans are a net source.

iii Summing over all ocean regions gives a net oceanic uptake of less than 1 Gt C y^{-1} so the atmospheric carbon budget must be balanced by a net uptake of over 1 Gt C

y^{-1} assumed to be into the terrestrial biota.

iv If the net biotic uptake is due to enhanced plant growth in response to increased atmospheric CO_2, then this process would be expected to occur both in the northern latitudes (where the atmospheric data indicate a CO_2 sink) and in the tropics. Such a tropical uptake would tend to cancel the carbon release from tropical deforestation. This could explain why the atmospheric CO_2 data show little evidence of a tropical source beyond the expected ocean source [6], [9], [10].

3. IMPLICATIONS

The first possibility that we must consider is that the Tans et al. analysis mis-interprets the data in some way (e.g. errors in the transport models) and that the conventional view of the atmospheric carbon budget is correct. If however we accept the Tans et al. analysis as basically correct then we need to distinguish between two rather distinct possibilities. The first is that the low oceanic uptake has applied over the whole of the industrial period. This seems to be hard to reconcile with carbon cycle models, particularly with regard to the oceanic uptake of ^{14}C from nuclear testing. The second possibility is that the low oceanic uptake is a recent phenomenon and that the ocean mixing processes have changed, possibly due to climatic changes. However the size of the changes involved seem to be far too large for this to be likely. Clearly, additional information to resolve these questions is highly desirable.

In either case the atmospheric carbon budget proposed by Tans et al. [8] implies a major role for the terrestrial biota. If this is true then we need to answer the question of why the biota have responded in such a way that the rate of CO_2 increase in the atmosphere has represented close to a fixed proportion ($\approx$0.55) of the fossil carbon release over the last 30 years of accurate CO_2 measurements. This relative constancy is particularly suprising if we have had a period of changing sink processes in which the biota have in part replaced the oceans as the major sink of CO_2. Indeed Keeling et al. [14] (see their Fig. 38) find that the observed departure from constancy of the airborne fraction is smaller in magnitude and opposite in sign to the variation predicted from a conventional ocean model. They conclude that the model biotic release that they use after 1970 is an underestimate. A possibility that they did not consider is that the oceanic or biotic uptake has been decreasing.

The atmospheric data are unclear as to whether there has been a change in the role of the oceans. Comparison of the data used in the recent inversion [9] with the data analysed by Pearman and Hyson [13] whose results supported the conventional view by having a strong southern ocean sink, indicate that the concentration difference across the southern hemisphere was greater in the data for around 1980 than in the more recent data. We are unable to say whether this represents a real change in the atmosphere or whether the difference is spurious, reflecting calibration problems in the early part of some of the records. It should be noted that in the two long records from the South Pole and Mauna Loa, Hawaii, Keeling et al. [14] find that the concentration difference between these two sites grew from 1958 to about 1974 and remained nearly constant since then. This is qualitatively what would be expected from the pattern of fossil fuel usage with unchanging oceanic uptake processes although there may be a contribution from a decrease in the strength of the southern hemisphere ocean sink. The timeing of the change is somewhat different from that suggested by the data comparison noted above.

4. OTHER EVIDENCE

Ice-core deconvolutions: As noted above, the oceanic uptake of CO_2 at any time will depend on the carbon gradients within the oceans that will have been established by past changes. Even if we take a particular carbon cycle model as being exact, we cannot determine the atmospheric carbon budget at a single point in time. The oceanic uptake (and thus the net biotic exchange which is obtained from the atmospheric budget) must be analysed over the whole of the period for which changes have occurred, in this context the whole of the industrial period. This requires atmospheric CO_2 data for the whole of the industrial period.

Such data have become available from measurements of the composition of air bubbles trapped in polar ice [15], [16]. With such data, a carbon cycle model can be used to derive the net source of CO_2 into the atmosphere/ocean system. The net biotic source is obtained by subtracting the fossil source from the source calculated by the model. Such a deconvoluton calculation has been performed by Siegenthaler and Oeschger [7]. As noted above their release estimates showed a peak of net release from the biota around 1900. Furthermore their $\delta^{13}C$ data from the ice core, combined with modern observations, was consistent (to within the rather large measurement precision) with the $\delta^{13}C$ values calculated by their model when using the sources obtained by the deconvolution of the concentration data.

Land-use change analysis: As noted above, the interpretation of the current atmospheric carbon budget will depend on the history of past changes. The most comprehensive attempt to provide direct estimates of the history of biotic sources over the last century is the work of Houghton et al. [17]. Their estimates are based on compilations of land use changes combined with simple parameterisations of the history of carbon fluxes that follow each type of change.

Houghton (at Hinterzarten CO_2 conference) has emphasised that this approach does not take into account biotic carbon fluxes due to changes in ecosystem quality when these are not associated with a change in land use. Processes such as eutrofication, forest dieback, CO_2-induced growth, responses to climatic variations and many others can not be estimated by this approach.

The time history of the releases obtained by Houghton et al. is quite different from the biotic releases estimated by deconvolution of ice-core data. The large total release obtained by Houghton et al. prompted the search for ocean models that could account for the uptake of greater amounts of carbon. Enting and Mansbridge [18] showed that such an approach could not resolve the difference between the ice-core data and the direct estimates of biotic releases. Specifically they used a linear programming analysis to show that no possible linear steady-state ocean model could be consistent with both the ice-core data and the direct estimates. Enting and Mansbridge favoured the possibility that there was an error in the estimates fo release from the biota. However another possibility that must be considered seriously is that it is the assumption of a steady-state ocean that may be unjustified. The discrepancy between the ice-core data and the direct estimates could be reduced, probably to within the estimated errors on each data set, if part of the 19th century CO_2 increase was attributed to a recovery from a perturbation from the little ice age. This was discussed in more detail at the 1988 Lake Arrowhead meeting (Enting, unpublished) but there is very little data with which to test the suggestion.

Isotopic information: The uptake of CO_2 by the terrestrial biota discriminates against the heavier carbon isotope, ^{13}C, so that biotic material is depleted in ^{13}C. When the carbon returns to the atmosphere, the isotopic composition is essentially unchanged. Thus exchanges of biotic carbon have a characteristic isotopic signal which differs from the isotopic signal of air-sea exchanges.

The main signals that are apparent in $\delta^{13}C$ data are a long-term global trend, an interhemispheric gradient and a spatially varying seasonal cycle. The modelling studies by Enting and Pearman [4], [20] suggest that the calculated rate of change of $\delta^{13}C$ is quite insensitive to the history of the release of carbon from the biota once the CO_2 concentration is constrained to follow the observations. The seasonal cycle seems to simply reflect the seasonal biotic variation. The interhemispheric gradient has the potential to help distinguish between oceanic and biotic sinks. However the actual data does not seem to be consistent with either, showing a relative depletion of atmospheric $\delta^{13}C$ in high northern latitudes. If this represents a new class of source which cannot be independently estimated, then the additional unknown effectively removes the possibility of separating oceanic and biotic sources. It is, of course, possible that the $\delta^{13}C$ anomaly is a reflection of the same anomaly that is causing us the revise the atmospheric carbon budget. There are rather large differences in the amount of interannual variability in the two available sets of atmospheric $\delta^{13}C$ time series [14], [21].

Tree rings: If the terrestrial biota are acting as a sink of carbon on a relatively long term, then it would be expected that this might be reflected in tree-ring growth. There are clearly enormous difficulties in detecting any such signal reliably, let alone using it to provide a quantitative estimate of extra biotic CO_2 uptake. Apart from direct growth, it is conceivable that the $\delta^{13}C$ levels in tree rings might reflect the physiological effects leading to extra growth [22].

Time Series Analysis: In this section, we consider studies that attempt to determine aspects of the biotic influence on atmospheric CO_2 from analysis of the CO_2 time series. In this regard it should be noted that the claim by Elliott et al. [19] that time series analysis shows the biotic release to be small is unjustified. Their analysis make unjustifiable approximations and is to some extent circular (for further discussion see [20], [23]).

There have been a number of studies of the seasonal cycle at Mauna Loa, generally looking for changes in amplitude that would presumably reflect a change in the activity (and therefore possibly in the size) of the terrestrial biota. The earliest study by Hall et al. [24] in 1975 failed to find any significant systematic change. Later, Pearman and Hyson [25] detected an overall increase in amplitude. The study by Cleveland et al. [26] showed that the change in amplitude occurred mainly towards the end of the record that he analysed, thus explaining why Hall et al. found no change when looking at the earlier data. Later studies [27], [28] have looked at the year-to year variability in the cycle using complex demodulation and have indicated that most of the change in amplitude took place between 1975 and 1980 and that there has been little systematic change since that time.

Houghton [29] has looked at the metabolic changes required to produce the observed amplitude changes and has concluded that they are implausibly large.

5. CONCLUDING REMARKS

On the basis of published estimates over the last decade, it is clear that the role of the terrestrial biota is the most uncertain part of the atmospheric carbon budget. It is not clear whether this represents a major problem with current models (e.g. incorrect transport or a 'missing sink') or a failure to successfully model carbon transfers to and from the terrestrial biota. This unsatisfactory situation is highlighted by several conflicts in the (model-interpreted) results of measurement programs. The removal of this major uncertainty in the atmospheric carbon budget is a pre-requisite for any predictions of environmental changes due to the greenhouse effect. There is an urgent need for a close interaction between development of atmospheric and biotic models and new measurement programs in order to clarify current uncertainties.

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