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Seasonal sources and sinks of atmospheric CO_2 Direct inversion of filtered data

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ABSTRACT

A two-dimensional atmospheric transport model with transport fields derived from a GCM is used to perform the inverse calculation of determining surface CO_2 sources from surface concentration data. The concentration data are filtered spatially and temporally with a minimum period of 6 months and a maximum spatial wave number of 5 in order to suppress the unbounded error amplification that occurs in such inverse problems. The distribution of sources and sinks is consistent with recent results concerning oceanic uptake of CO_2. The results also show an additional northern hemisphere sink that is interpreted as additional biotic growth and a seasonal tropical source that may represent seasonal burning of cleared biomass.

1. Introduction

The problem of identifying the spatial and temporal distribution of sources and sinks of atmospheric CO_2 on the basis of observed variations in concentrations is of intense current interest. It is hoped that identifying the locations and times of occurrence of CO_2 sources will help identify the biological and geophysical processes involved. For these reasons, an increasing number of stations world-wide are involved in obtaining the requisite concentration data. Although much is known about the sources and sinks of CO_2 a number of important questions remain unanswered concerning, for example:

(i) the net source strength due to deforestation in tropical regions;

(ii) the seasonal variation in air-sea exchange of CO_2 due to variations in wind-speed, temperature and depth of the mixed layer;

(iii) influences of marine biotic activity on air-sea exchange of CO_2.

In addition to addressing questions directly related to CO_2, the methodology of deducing source strengths from concentration data is of interest for studies of other atmospheric constituents such as CH_4.

Questions of techniques are of some importance because the problem of deducing the distribution of surface source strengths of CO_2 given surface concentration data and assuming an atmospheric transport model is an example of the type of ill-posed inversion problem that occurs in many branches of geophysics (Enting, 1985a). Indeed recognition of the difficulties arising from the ill-posed nature of the inversion problem goes back to Bolin and Keeling (1963). The problem is ill-posed (i.e. the solution depends discontinuously on the data) because arbitrarily small errors in the data can be magnified by arbitrarily large amounts in the solution. Similar magnifications will apply to errors in the problem formulation (i.e. errors in the atmospheric transport model in this case).

Bolin and Keeling (1963) modelled meridional transport as a one-dimensional diffusion process. Enting (1985a) noted that for more realistic two-dimensional models the error amplification was less severe than implied by Bolin and Keeling. The relevant results are described in more detail

below. Because Bolin and Keeling were using a poor model with severe error amplification, the resolution that they could achieve was limited more by their model than by the relatively small amount of CO_2 data available in 1963. In contrast the studies presented here, using a model with smaller errors and a less severe error amplification, have their resolution limited by the variability of the data. Further discussion of the problem of deducing surface sources from surface concentration data is given by Newsam and Enting (1988).

The problem addressed in this paper is the derivation of zonally averaged source strengths as a function of time, assuming that the sources have a strictly periodic annual cycle. The limitations on the data arise from longitudinal and interannual variability that restricts our ability to define concentration values that are precisely representative of their latitude and season. Previous inversions of the CO_2 data have been the original work of Bolin and Keeling (1963) and a preliminary account of the present study given by Enting and Mansbridge (1987a). An inversion, restricted to the tropics, was performed by Keeling and Heimann (1986) using a diffusive model calibrated by Heimann and Keeling (1986). More recently, an independent inversion calculation (P. P. Tans, private communication) has produced results broadly similar to those presented here.

An alternative approach to the study of atmospheric CO_2 variations is to model the source/sink processes and use a transport model to calculate the concentrations. These are then compared to observations. A major example of this type of study is the three-dimensional modelling study by Fung et al. (1983) (see also Fung, 1986; Heimann et al., 1986). The study by Pearman and Hyson (1980) is a hybrid of the source-modelling and source-deduction approaches. The strengths of biologically plausible source variations were adjusted in a "trial-and-error" fashion in an attempt to fit the concentration data. This approach has been extended by Pearman et al. (1983) and Pearman and Hyson (1986). The limitation of the "forward-modelling" approach is that agreement between observed and calculated concentrations is only a weak test of the source model. The difficulty is that the "forward" problem of deducing concentrations from sources suppresses errors in the sources by a factor which is the reciprocal of the amplification factor by which the "inverse" problem amplifies similar errors when deriving sources from concentrations. Craig and Brown (1986) give a useful discussion on the methodological implications of these general properties of inverse problems.

The layout of the remainder of the paper is as follows: Section 2 describes the numerical model of atmospheric transport and the way in which it is used in this study. Section 3 discusses the conditioning of the inversion problem and the resolution that can be expected. Section 4 gives the results of the inversion and considers their sensitivity. Section 5 discusses various features of the results. The concluding Section describes some possibilities for future improvements to the inversion procedure.

2. The transport model and its use

2.1. The model

The technical details of the transport model have been described by Enting and Mansbridge (1986) and a number of preliminary tests have been described by Enting and Mansbridge (1987a). The model is a finite difference representation of a zonally-averaged atmosphere. It is implemented with both horizontal and vertical resolution being adjustable parameters and furthermore the vertical co-ordinate may be either pressure or height. The horizonal co-ordinate is sine(latitude) giving an equal-area grid. The differencing scheme is essentially that described by Miller et al. (1981); it is accurate to second-order in the grid spacing. The calculations presented by Enting and Mansbridge (1987a) show that with this second-order scheme the results for both forward and inverse calculations are essentially independent of the horizontal resolution but are noticeably dependent on the vertical resolution. An Euler predictor-corrector scheme is used for time-stepping. The transport fields that are required are: a scalar stream function ψ, describing the advection, and a symmetric diffusion tensor K. The model accepts transport fields as inputs and performs appropriate tensor transformations (Enting and Mansbridge, 1986) so as to use fields appropriate for whichever co-ordinate system is in use. Non-dimensional units are used whenever

possible: time is in years, constituents are specified in terms of mixing ratios and height is in terms of scale heights, i.e., the distance over which an e-fold reduction in pressure occurs. Also, when calculating source strengths we express our results as a release rate per unit area with the area of the earth taken as 1, rather than using release rate per zone, so that our definitions are independent of the model resolution.

The model can be regarded as implementing numerical solutions of a set of differential equations describing the evolution of concentrations, c_i at grid point i, in response to a set of sources, s_i with transport coefficients A_{ij}.

$$\frac{dc_i}{dt} = \sum_j A_{ij}(t)c_j(t) + s_i(t). \quad (1)$$

The model may be run in either of two standard ways. The first is the modelling approach in which the transport equations are integrated using a given set of source strengths. The second is to run with a specified lower boundary condition and to deduce the source strengths that are needed to produce the concentrations (Enting, 1984). The latter mode of operation is used in the calculations presented in this paper. These calculations use 10 (equal area) zones, 8 equally spaced pressure levels and a time step of 0.001 years.

The concentration fields we use assume strictly periodic seasonal cycles at all latitudes, superimposed on a fixed inter-hemispheric gradient and a linear concentration increase that is the same at all sites. We chose this form of concentration variation because it leads to a relatively simple Green's function representation that enables us to prove that the source-deduction problem will have a unique, strictly periodic, solution. The proof generalizes that given by Enting (1985b); the details will be given elsewhere. The use of periodic variations also enabled us to identify the period required for transient effects to become negligible after starting our integrations from a uniform initial concentration. Although mathematical convenience motivated our choice of strictly periodic sources, it should be noted that the assumption of a linear trend and fixed interhemispheric gradient corresponds to a fixed annual mean net carbon source. This is a good approximation for the fossil carbon release in the period around 1980 during which most of the concentration data were obtained.

2.2. *Transport fields*

The standard input to the model uses a truncated spectral representation to describe the variation in space and time of ψ and each component of K. Defining our fields in this way enables us to vary the spatial resolution of the model smoothly. On input to the model, the spectral expansions are evaluated at each grid point and any necessary tensor transformations are applied. The spectral representation of the time variation is retained so that the model uses coefficients that vary smoothly with time.

Our transport coefficients are based on calculations by Plumb and Mahlman (1987). They obtained a set of fields that give a two-dimensional representation of tracer transport in the three-dimensional GFDL general circulation model.

Our spectral representations were obtained by least-squares fits to the fields computed by Plumb and Mahlman. When used in the model, lower bounds were applied to ensure that the diffusion tensor remained positive definite. This use of bounds removed negative values arising from both instabilities in the original calculations of the fields and Gibbs-type fluctuations in our spectral representation. Our use of the spectral representation tends to smooth the transport fields and in particular it greatly reduces the sharpness of the tropopause. An additional smoothing and shifting of the tropopause was introduced by the procedure used to calculate the transport fields from the GCM output (R. A. Plumb, personal communication). The calculations described by Enting and Mansbridge (1987a) show that, as a consequence of this smoothing, the quantitative description of stratosphere to troposphere transport is poor, although somewhat better for ^{14}C than the earlier model of Pearman et al. (1983).

Enting and Mansbridge (1987a) plot the values of each of the transport fields as determined by the spectral expansion for February and August. The present study uses fields that differ slightly from these. The vertical diffusion now includes a vertical eddy-diffusion coefficient as used in the original GCM but which was not included in the plots shown by Enting and Mansbridge (1987a). Enting and Mansbridge plotted a mass stream-

function that was fitted directly to the mass stream-function of Plumb and Mahlman. The present study uses a mass stream-function chosen so that the velocity stream-function was a least-squares fit to that of Plumb and Mahlman. The effect of the change is that the present form gives greater weight to the stratosphere and so improves the resolution of the tropopause. This is important for studies involving transport between the stratosphere and troposphere but makes little difference to the present calculations. We have not sought to improve our fit to this aspect of the Plumb and Mahlman data any further because of the limitations of their transport fields noted above.

3. The conditioning of the inversion

The inversion of the space-time distribution of CO_2 concentrations in order to deduce the strengths of surface sources and sinks is an example of a poorly-conditioned inverse problem. Such problems are common in many branches of geophysics but there has been relatively little work on this aspect of atmospheric constituent studies. The difficulties in deducing CO_2 sources were noted by Bolin and Keeling (1963) who concluded that "no details in the distribution of sources and sinks are reliable". However little of the subsequent published work on this problem reflects serious consideration of this warning.

The difficulties with inverse problems arise through the (unbounded) amplification of small errors in both the data that is being inverted and the model that is being used for the inversion. The rapid growth in the amplification of errors puts strong constraints on the resolution with which such inversion calculations can be performed. In order to illustrate the essential features of such inversion problems we have repeated some of the one-dimensional analysis performed by Bolin and Keeling (1963) using modern concentration data.

The concentrations (in ppmv) are expanded as:

$$c(x, t) = 1.5t + \sum_{j=-2}^{2} \exp(2\pi ijt) \sum_{k=0}^{N} a_{jk} P_k(x) \qquad (2)$$

where the $P_k(x)$ are Legendre polynomials and the x co-ordinate represents sine(latitude) and $i = \sqrt{-1}$.

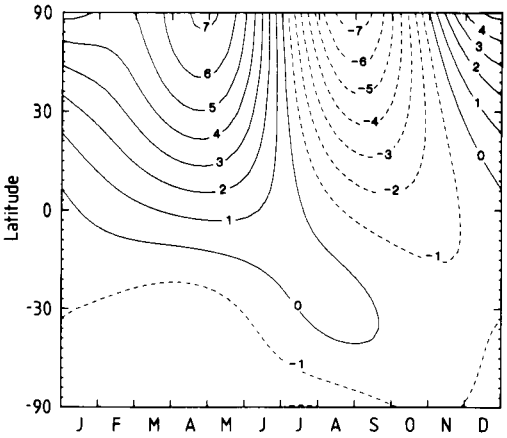

Fig. 1. Low resolution representation of the seasonal and latitudinal variation in CO_2 using the composite data set described by Enting and Mansbridge (1987a). The spatial variation is expanded using Legendre polynomials up to P_3; the temporal variation is expressed as a Fourier expansion up to the semi-annual component. A linear trend has been removed. Units are ppmv.

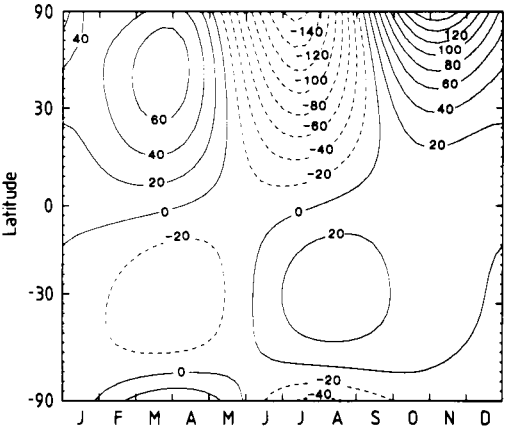

Fig. 2. Sources deduced from the smoothed concentrations shown in Fig. 1, plus the linear trend, using the one-dimensional diffusion model. Units are Gigatonnes of carbon per unit area with the total surface area of the earth taken as 1.

The sources are deduced by using a one-dimensional diffusion model:

$$\frac{\partial c}{\partial t} = \frac{K}{R^2} \frac{\partial}{\partial x}\left((1 - x^2)\frac{\partial c}{\partial x}\right) + s(x, t), \qquad (3)$$

where R is the radius of the earth and the diffusion coefficient K is assumed to be 2×10^{10} cm^2 s^{-1}.

The solution to these equations is:

$$s(x,t) = 1.5 + \sum_{j=-2}^{2} \exp(2\pi ijt) \sum_{k=0}^{N} \times a_{jk}\left[2\pi ij + \frac{K_2}{R}k(k+1)\right] P_k(x). \quad (4)$$

Fig. 1 shows a representation of $c(x,t)$ based on the NOAA/GMCC flask data (Kohmyr et al., 1985) using expansion (2) truncated at $N = 3$. Fig. 2 shows the corresponding sources as determined by Eq. (4). The sources deduced give a plausible representation of broad features of CO_2 sources such as opposite phases in northern and southern hemispheres, larger amplitude seasonal sources in the northern hemisphere and a double peak in northern hemisphere releases, presumably due to decreased respiration in midwinter.

Figs. 3, 4 show the $c(x,t)$ and the corresponding $s(x,t)$ calculated using the $N = 5$ truncation. While the representation of $c(x,t)$ is improved, particularly in the tropics and southern hemisphere, the sources $s(x,t)$ are quite unreasonable. What is happening is that the $k(k+1)$ factor in (12) gives a rapidly growing amplification of small-scale errors in both the model (3) and the data $c(x,t)$. By far the most important of these two problems is the amplification of errors in the transport model since the examples show that attempting to reduce the errors in the data actually gives worse results because the model is not valid on the smaller space scales. Inversions using the one-dimensional diffusion model are subject to an

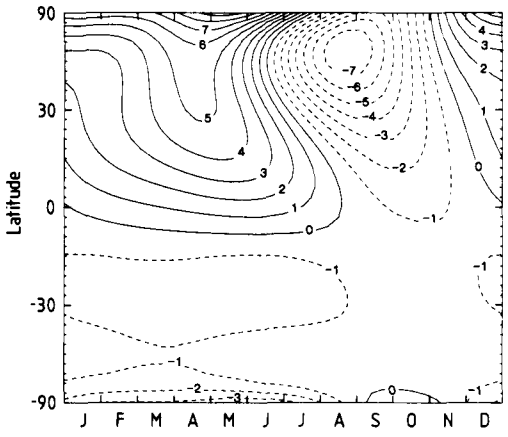

Fig. 3. As for Fig. 1, but with the spatial expansion extented to P_5.

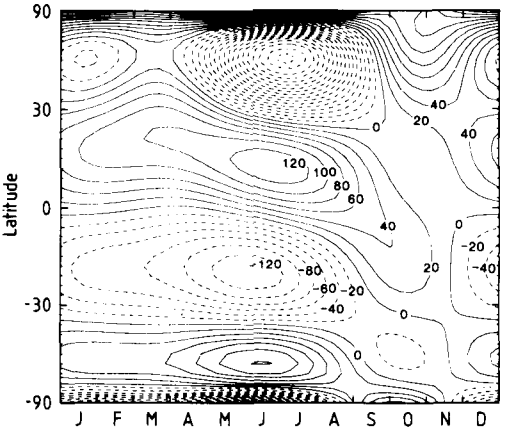

Fig. 4. Sources deduced from the concentration data shown in Fig. 3 (plus linear trend), indicating that the inversion becomes unstable due to catastrophic amplification of errors in the transport model.

inherent limit on their resolution. Further calculations, not presented here, show that these conclusions are not changed if different values of K are used. Indeed the same catastrophic error amplification remains even if we try to impove the accuracy of the model by having a spatially varying diffusion coefficient $K(x)$ as estimated by Czeplak and Junge (1974).

In assessing the limits of resolution in an inversion calculation, four factors are involved. These are the rate at which errors increase with spatial wavenumber k in the inversion, the size of errors in the model, the size of errors in the data to be inverted and the tolerable size of errors in the solution.

The rate of growth of errors as a function of k can be assessed for the two-dimensional model by calculating the response of the model to sources specified by special functions.

In the solution of the one-dimensional diffusion model the expansions have the property that each source component can be attributed to precisely one concentration component. For a general transport model, a singular value decomposition of the appropriate Green's function matrix would produce two sets of functions (one for the concentrations and one for the sources) with the model giving a one-to-one mapping between the two sets. While this approach is in principle the best way to study the conditioning of the problem, in practice a good

understanding of the conditioning can be obtained more easily by choosing sets of functions for which mapping is nearly one-to-one in the sense they give a basis in which the diagonal elements of the Green function matrix are dominant.

In our two-dimensional inversion calculation we follow Enting and Mansbridge (1987a) and represent the concentrations by an expanding variations in time using terms involving $\cos(2\pi jt)$ and $\sin(2\pi jt)$. The spatial variations are expanded using $\cos(\frac{1}{2}\pi k(x+1))$ with $x = \sin(\text{latitude})$. This spatial expansion can be regarded as a Fourier series representation of a periodic system where the repeat unit consists of the north-south variation followed by its reflection. This representation give functions that are continuous at the poles and so the Fourier expansions converge more rapidly than if the north-south variation was the basic repeat unit.

These functions are used for expanding both sources and concentrations. Fig. 5 shows the responses to sources with a sinusoidal variation of period one year as a function of k, the index describing the spatial variation. (The spatial resolution was extended to 20 zones for these calculations). The values plotted are the amplitudes of the concentrations. No information about the phase of this response is shown. The amplitude of the response was found to be virtually independent of the phase of the source. It will be seen that there is a regular k^{-1} decay in the forward problem giving a linear growth in error amplification in the inverse problem. Thus, as noted by Enting (1985a), when a more realistic transport model is used, the inversion problem is better-conditioned than would be suggested by the examples using the one-dimensional diffusion model.

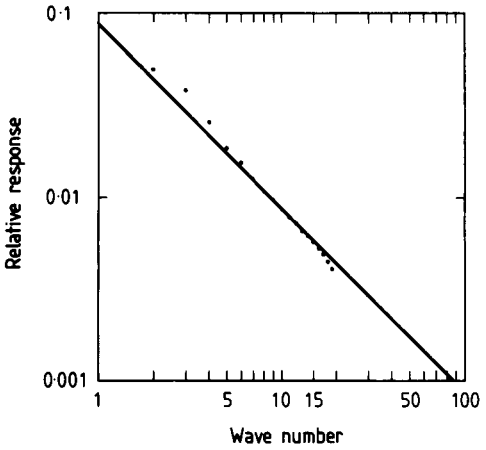

Fig. 5. Elements of the Green's function defining the behaviour of the two dimensional transport model. The response shown is the amplitude of the component with a 1-year period and spatial wave number k, given a source with a 1-year period and wave number k. The amplitude of the response is virtually independent of the phase of the source source. The phase of the concentration response is not shown. The k^{-1} behaviour shows that inversions using this model will be more stable than inversions using the one-dimensional diffusion approximation.

It is rather difficult to obtain reliable estimates of the size of errors in the model. The tests described by Enting and Mansbridge (1987a) suggest that the model is giving reasonable results for the large-scale features. The k^{-1} behaviour of the Green's function elements appears to be a (primarily geometric) characteristic of the relation between surface sources and surface concentrations in two (and three) dimensional models because models with purely diffusive transport also show a k^{-1} behaviour in the relation between surface sources and surface concentrations (Newsam and Enting, 1988). Surface sources and vertically averaged concentrations are related by a k^{-2} dependence. (The extra factor of k^{-1} arises from the k-dependent vertical attenuation of surface inputs.) Thus, the primary source of error in the Bolin and Keeling analysis is equating surface data to vertical averages. The same error may also cause problems with the Heimann and Keeling (1986) analysis, as was noted by those authors. Newsam and Enting (1988) propose an approximate correction to remove such errors. By contrast, the above analysis suggests that the k^{-1} behaviour applies to the real atmosphere and so the size of the errors in our advective-diffusive model is at worst of order k^{-1}. Since the inversion gives an amplification proportional to k, it is to be expected that model errors will make approximately equal contributions to each Fourier component in an inversion calculation. However, when the one-dimensional diffusion model is used the errors are of order k^{-1}, i.e., the difference between a correct k^{-1} dependence and the incorrect k^{-2} dependence. Since the amplification grows as k^2 the result is that the contributions from model errors grow linearly with k when performing inversions with the one-

Table 1. *Coefficients used to define the space-time variation of CO_2 equivalent to eq. (5), but using trigonometric functions in place of complex exponentials. The linear trend is 1.5 ppmv yr^{-1} as specified in the equation*

	1	cos $2\pi t$	sin $2\pi t$	cos $4\pi t$	sin $4\pi t$
1	—	0.334	1·810	0.107	−0.636
$\cos(\pi(x+1)/2)$	−1.490	−0.865	−3.054	−0.220	1.058
$\cos(2\pi(x+1)/2)$	−0.294	0.850	0.819	0.415	−0.553
$\cos(3\pi(x+1)/2)$	0.134	−0.264	−0.148	−0.401	0.085
$\cos(4\pi(x+1)/2)$	0.338				
$\cos(5\pi(x+1)/2)$	−0.115				

dimensional model and equating surface concentrations to vertical averages.

The resolution of the data can be interpreted in terms of a regression analysis fitting the observed data to an expansion of the form described above. This can be compactly written as:

$$c(x, t) = 1.5t + \sum_{j=-2}^{2} \exp(2\pi ijt) \sum_{k=0}^{N(j)} a_{jk} \cos(\tfrac{1}{2}\pi k(x+1)) \qquad (5)$$

but when listing the coefficients in Table 1, we revert to the use of trigonometric functions of time.

The NOAA/GMCC flask data (Kohmyr et al., 1985) were not available when the calculations described by Enting and Mansbridge (1987a) were performed. Consequently a composite data set was analysed. We have continued to use the composite data set for reasons of direct comparability, after noting that the differences from the GMCC data set are in fact quite small at the resolution considered here. The interhemispheric gradient is fitted to earlier GMCC data which gave annual means (Bodhaine and Harris, 1982). This ensured that differences in calibration scales did not affect the representation. The seasonal cycle was fitted to a composite set of 13 surface sites with 4 or more years of data using a regression analysis described by Enting and Mansbridge (1987a). The coefficients in eq. (5) were estimated by fitting regression equations to the time variation at each site. These sets of regression coefficients for corresponding time variations were then fitted to the specified spatial variation.

The expansion in the time domain is truncated at $|j| = 2$ because almost none of the sites show statistically significant components with periods less than 6 months, Barrow being the main exception (see for example Thompson et al., 1986). From our regression analysis the appropriate spatial truncation was determined to be at $k = 5$ for $j = 0$ and at $k = 3$ otherwise. These truncations represent a smoothing of the data in order to suppress noise that would otherwise be amplified in the inversion process. Our choice of cutoff is the same as that used by Bodhaine and Harris (1982) and Pearman and Hyson (1986) in constructing smoothed representations of the interhemispheric gradients, but we have used a smoother representation of the seasonal cycle. (Our technical report, Enting and Mansbridge, 1987a, also reports results with even greater spatial smoothing of the seasonal variation.) The scatter shown in Figs. 4 and 5 of Pearman and Hyson (1986) supports our belief that a more detailed representation is not justified by the available data.

In considering the appropriate truncation in the spatial domain, it is worth examining the analogous problem of filtering time series. There, the optimal filter for removing the noise will be the same regardless of whether the noise reduction is required for direct estimation of a signal or for some poorly conditioned "inverse" calculation such as numerically differentiation of the signal, (Enting, 1986). However inverse problems are more sensitive to degradation of the results due to sub-optimal smoothing.

The discussion above suggests that the resolution of the inversion calculation will be limited by the noise in the data rather than the limitations of the model. In actual fact, the distinction is not quite so clear-cut. Many of the limitations of the data arise from our requirement for strictly periodic, zonally averaged quantities because this reflects the form of our model. It

seems probable that the existing data would support a higher resolution inversion using a three-dimensional model with historically accurate interannual variations in transport. However, given the limited longitudinal distribution of observations, such an inversion would still need to be severely constrained in order to produce stable results.

4. Results and sensitivity studies

The smoothed representation of the seasonal cycle in concentration data is shown in Fig. 6. It can be compared to the more complete representation of the space-time variation (including interannual variations) of the GMCC CO_2 data shown in Fig. 8 of Harris and Nickerson (1984). The sources derived from the full data set (i.e. the variations from Fig. 6 plus interhemispheric gradient plus linear trend) using the two-dimensional model are shown in Fig. 7. In order to represent these in a resolution-independent manner the area units have been chosen so that the total surface area of the earth is 1 as for Figs. 2 and 4. The mass units are gigatonnes of carbon and the time units are years. Fig. 8 shows the spatial variation of the deduced annual mean source strength together with the fossil fuel release rate (Rotty, 1983), and the difference between these quantities.

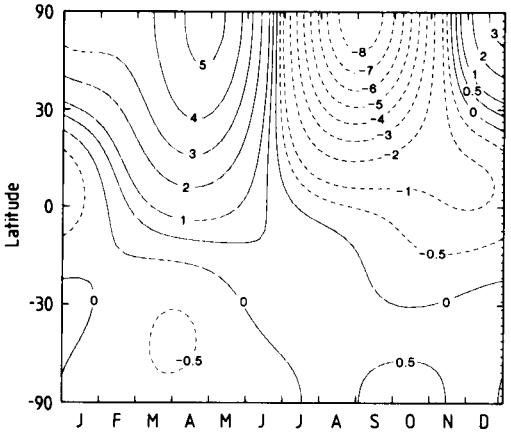

Fig. 6. Seasonal variation of CO_2 concentrations from the function defined by eq. (5) with coefficients from Table 1 but excluding mean interhemispheric gradient and secular trend.

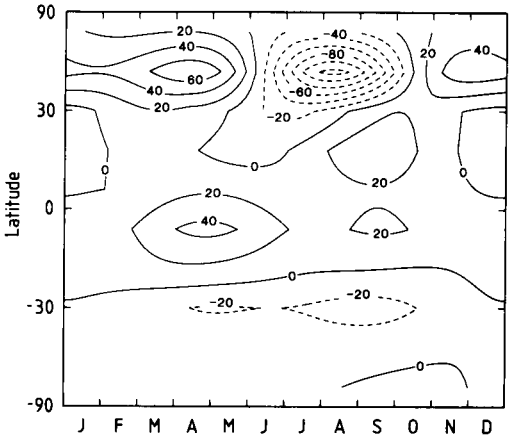

Fig. 7. Sources deduced from the concentration data shown in Fig. 6 (plus the mean interhemispheric variation and global linear trend), using the two-dimensional transport model. Units as for Fig. 2.

The main features obtained from the inversion calculation are:

(i) the difference between the fossil carbon release and the annual mean net source/sink strength shown in Fig. 8 indicates a predominantly mid-latitude ocean sink for the southern hemisphere;

(ii) there is relatively little seasonal variation in the source strengths in high southern latitudes; the maximum uptake at latitudes around 30°S occurs in spring;

(iii) the difference between the annual mean net source and the fossil carbon release gives a mid-latitude sink in the northern hemisphere, with a magnitude very similar to the southern hemisphere sink;

(iv) the northern hemisphere source peaks in fall and spring;

(v) there is a relatively strong seasonal contribution from the tropics.

In order to assess the influence of uncertainties in the transport coefficients we performed several sensitivity studies in which the transport coefficients were changed. In view of the concerns about the global CO_2 budget, we concentrated on assessing the changes to the annual mean source strengths shown in Fig. 8. For the three cases in which ψ, K_{pp} and K_{yy} were reduced by 10%, the maximum changes in any zone were 1.27, 0.42 and 0.64 Gt/yr/earth-area respectively. Presumably this relatively small sensitivity re-

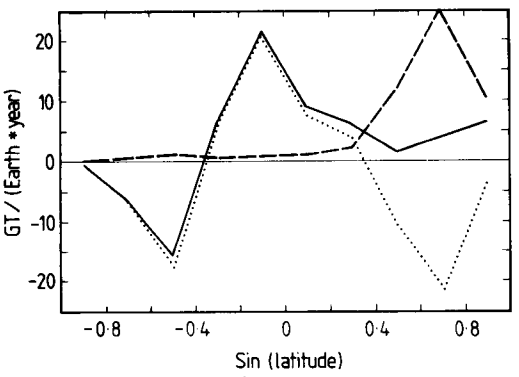

Fig. 8. Annual mean of the source strengths shown in Fig. 7. (solid) with the spatial variation of fossil CO_2 sources from Rotty (1983) shown (dashed) for comparison. Each is converted to Gigatonnes per year per unit area as for Fig. 2. The difference which corresponds to oceanic plus biotic contributions is shown as dotted.

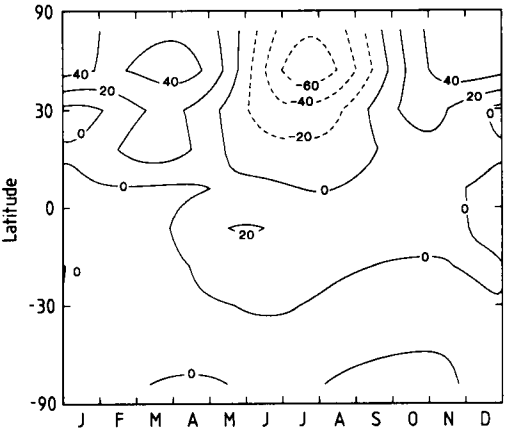

Fig. 9. Direct inversion using an approximation to the transport used by Pearman and Hyson (1980, 1986). The results are qualitatively similar to those estimated by Pearman and Hyson (1980). Units as for Fig. 2.

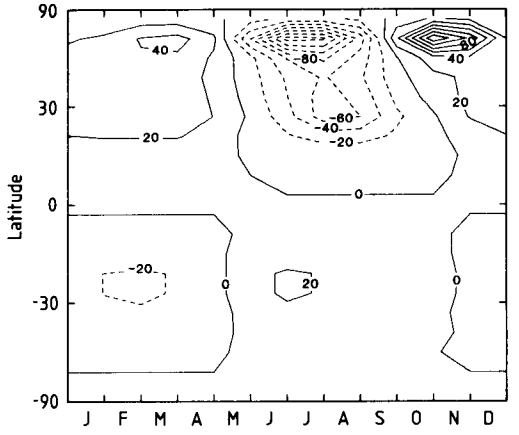

Fig. 10. Biotic CO_2 source used by Pearman and Hyson (1986), shown for comparison. Units as for Figs. 2, 7 and 9.

flects the fact that our original smoothing of the concentration data has removed the more rapidly varying modes for which even small errors in the model would give large errors in the deduced sources. However our results were found to be rather more sensitive to the resolution and representation used for the vertical variations in the transport fields. This behaviour is consistent with that observed in our preliminary tests of the model (Enting and Mansbridge, 1987a). Its significance is currently under investigation.

In order to consider the effect of larger errors in the model, we produce the results of an alternative inversion. This uses the Eulerian advection of Oort (1983) together with the diffusion coefficients of Hyson et al. (1980). Following Enting and Mansbridge (1987a) we have, for the purpose of this comparison, doubled K_{yy} in order to approximately simulate the numerical diffusion that is present in the model of Hyson et al. due to their use of a first-order advection scheme. This is a very crude correction that is chosen so as to be most accurate in the tropics where the role of diffusion is most critical. The results are shown in Fig. 9. The magnitudes are broadly similar to the original values obtained by Pearman and Hyson (1980), but the details of the spatial distributions differ. For comparison we also show, in Fig. 10, the biotic sources used in the more recent modelling study by Pearman and Hyson (1986). This figure can not be precisely compared to the other source estimates because the oceanic component is omitted. All other source distributions presented here represent total sources, i.e., the sum of biotic, oceanic and fossil carbon sources and sinks. Some of the difference between Figs. 9 and 10 represents changes in the transport coefficients used by Pearman and Hyson. However, much of the change between Figs. 9 and 10 reflects attempts by Pearman and Hyson (1986) to obtain an improved representation of the seasonal variation at Barrow. The differences between Figs. 7, 9 and 10 emphasize the importance of the choice of model in obtaining reliable inversions. While

the effect of model errors grows sufficiently slowly to avoid the catastrophic error amplification shown in Fig. 4, differences between models are significant even at the $k = 5$ (or 3 for seasonal cycles) truncation suggested by the resolution of the CO_2 data.

This sensitivity in the results means that our inversions of CO_2 sources must be treated with caution. An additional reason for caution is that the spatial scale of many of the more interesting features is close to the limit of the resolution supported by the data.

5. Interpretation

We tentatively propose the following interpretation for the various features shown in Fig. 7. Enting and Mansbridge (1987a) give plots of the source strengths as functions of time for each of the 10 zones. These can be regarded as an alternative to the contour representation used in Fig. 7. (Strictly speaking, the earlier work uses a slightly different representation of the stream-function, ψ, but the differences in the sources are negligible.)

5.1. Ocean sinks

One notable feature, that presumably reflects the behaviour of the ocean, is that, after subtracting the fossil carbon contribution, the strongest annually averaged sinks occur in mid-latitudes rather than at high latitudes. A recent research review by Takahashi (1987) gives some support to this type of behaviour for the southern oceans. The CO_2 partial pressure difference between the atmosphere and the ocean, as determined from GEOSECS data, indicates that oceanic sinks of CO_2 occur primarily at mid-latitudes, (see for example Fig. 15 of Broecker et al., 1980). The northern oceans show higher pCO_2 differences than the southern oceans but this is insufficient to offset the effect of smaller areas. Thus the symmetric sink in Fig. 8 suggests the presence of other sinks in the northern hemisphere. The GEOSECS data for high latitudes was mostly obtained during the respective summers. Takahashi (1987) shows more recent results indicating that the Northwestern Pacific is a strong CO_2 source in winter and a weak source in summer. He also quotes recent observations showing similar behaviour in the North Atlantic and the Wedell Sea, Antarctica. This seasonal behaviour is the opposite to what would be expected solely on the basis of temperature changes. Takahashi attributes the observed behaviour to seasonal changes in upwelling. Seasonal changes in CO_2 solubility, upwelling and possibly in biota productivity in the ocean, as suggested by Pearman and Hyson (1986), provide competing effects that could explain the small net seasonal source variation noted above. Comparison of Figs. 7 and 9 (see also Figs. 9 and 10 of Enting and Mansbridge, 1987a) indicates that the strength of these mid-latitude sinks is sensitive to the transport fields.

5.2. Southern hemisphere seasonality

Fig. 7 shows that, outside of the tropics, the seasonal variation of southern hemisphere sources occurs mainly in zone 3 (23S to 37S). The peak release occurs in the (local) summer with a winter uptake peaking in August. The timing of the southern hemisphere source seems inconsistent with that of the terrestrial biota even after allowing for the possibility of moisture having a major influence on the timing of biotic growth. Pearman and Hyson (1986) noted the difficulty of reconciling southern hemisphere sources to observed concentrations. In particular they observed that attributing the seasonal sources to the terrestrial biota would require a ratio of net ecosystem production to biomass that was twice that obtained for the northern hemisphere. Pearman and Hyson suggested that seasonal growth of the marine biota might play an important role in the seasonal cycle of CO_2 in the southern hemisphere. This suggestion was followed by a study which used isotopic variations to distinguish between marine and terrestrial sources. A preliminary account of this work, confirming the importance of the marine biota in the southern hemisphere CO_2 budget is given by Francey et al. (1988). These modelling studies locate the active region further south than suggested by our calculations largely on the basis of isotopic studies (Francey, 1985) which indicate that the seasonal cycle in CO_2 at Cape Grim is largely due to direct exchange with the terrestrial biota. Given the low resolution of our inversion, the difference in the location of the southern sink should not be regarded as significant. The importance of the marine biota in determining seasonal CO_2 exchanges is also reflected in

Takahashi's discussion of pCO_2 variations in the northern Pacific.

5.3. *Northern hemisphere sink*

The plot of annual mean net source/sink strengths (Fig. 8) shows a mean sink for mid-latitudes in the northern hemisphere. This sink is of about the same strength as the corresponding southern hemisphere sink. The almost 2:1 ratio of ocean areas between latitudes 60 and 30 in the two hemispheres makes it highly improbable that the ocean sink strengths could be equal in the two hemispheres. Furthermore, the results shown by Takahashi (1987) suggest that the ocean sinks in the northern Atlantic occur at higher latitudes than the southern hemisphere ocean sinks. For these reasons, we propose that net biotic uptake is making a large contribution to the annual mean CO_2 sink in the northern hemisphere.

Two recent studies have shown a close connection between interannual variations in the seasonal cycle of CO_2 and interannual variations in biotic activity. Enting (1987) attributed the interannual variations in the cycle at Mauna Loa to biotic variations on the basis of an asymmetry in the correlations between peaks and troughs which reflected the difference between the timescales of CO_2 uptake and release. In a more direct study, d'Arrigo et al. (1987) showed a correlation between the variations in the seasonal cycle at Pt. Barrow and tree-ring widths from boreal forests. These two studies which associate interannual CO_2 cycle variations with biotic changes give significant support for interpreting the general increase in the amplitude of the CO_2 cycle at Mauna Loa as being due to an increase in the active biomass in the northern hemisphere.

The present results, together with a number of earlier studies cited below, lead us to suggest that the net changes in biotic carbon content are better represented by the estimates from Loucks (1980) than the estimates from Houghton et al. (1983). Loucks proposed that temperate forests became a net sink of carbon early this century and have remained a net sink of about 1 Gt yr^{-1}. Only for about the last 20 years do his estimates of the net tropical source become large enough to give a global net CO_2 source. In contrast, Houghton et al. estimate that the temperate forests are a smaller sink and only for the more recent period 1950–80.

There are a number of studies that indicate that various aspects of the estimates from Loucks (1980) give a better description of net biotic carbon releases than those of Houghton et al. (1983).

One important class of studies are those concerning the net global biotic carbon source/sink strength. Siegenthaler and Oeschger (1987) obtained estimates of the net biotic carbon release over the last 200 years by using a number of carbon cycle models to deconvolve the history of CO_2 changes obtained from polar ice cores. The absolute sources strengths were strongly model-dependent; the common feature of their deconvolutions was a recent increase in source strength after 1980. This behaviour disagrees with the estimates by Houghton et al. (1983) and agrees more closely with the estimates by Loucks (1980). (The deconvolutions by Siegenthaler and Oeschger would have the increase in the source beginning about a decade later than suggested by Loucks.) Many of the deconvolutions had the recent increase in biotic carbon release preceded by an increasing sink (or decreasing source) over the early part of this century as suggested by Loucks. (The exceptions are deconvolutions using the outcrop-diffusion model which has an exaggerated CO_2 uptake.) The steady decrease in biotic CO_2 release over much of this century was also obtained by Enting and Pearman (1987) by calibrating a carbon cycle model using techniques of constrained inversion without using any of the ice-core data. These estimates did not show any recent increase in the biotic release because the biotic release was expressed in terms of a low-resolution spline and the CO_2 data used in the calibration were restricted to the period 1959–1980. Again, by giving a general decrease in the net biotic source for much of this century, the estimates by Enting and Pearman (1987) are closer to those of Loucks than to those of Houghton et al.

As well as these model-dependent studies, there is a model-independent study by Enting and Mansbridge (1987b). That study showed that it is not possible to have a physically reasonable, linear, time-invariant model of ocean uptake that is consistent with both the history of CO_2 concentrations from ice-cores obtained by Neftel et al. (1985) and the estimates of biotic CO_2 releases obtained by Houghton et al. (1983). The model-

independence was achieved by expressing the uptake in terms of a response function which was arbitrary except for its sign and the signs of its first two-derivatives. Linear programming techniques were used to show that no oceanic uptake that was subject to these constraints could reconcile the ice-core data with the biotic release estimates from Houghton et al. (1983). Another attempt at obtaining model-independent constraints on biotic releases was described by Elliott et al. (1985). Enting and Pearman (1987) noted a number of problems with the method used by Elliott et al. which assumed a constant airborne fraction. It is, however, possible to use the generic inversion relations described by Enting and Mansbridge (1987c) to show that the approximation used by Elliott et al. is the first of a heirarchy of approximate inversions. Successive members of the heirarchy converge to show that the possible biotic release rates are confined to functions of the type obtained by Siegenthaler and Oeschger (1987) and so are in disagreement with the estimates by Houghton et al. (1983).

Other evidence that has been proposed in support of a temperate forest carbon sink concerns the change in amplitude of the seasonal cycle of CO_2. Pearman and Hyson (1981) detected an increase in the amplitude of the annual cycle at Mauna Loa and suggested that this could be due to changes in the temperate forest sink. While that interpretation could be consistent with a temperate forest contribution to the sink shown in Fig. 8, changes in the seasonal amplitude would suggest an increasing sink in recent years rather than Louck's estimate of a nearly constant temperate forest sink since about 1950.

As a final piece of evidence concerning the temperate sink, it should be noted that the modelling studies by Pearman and Hyson (1986) were best able to reproduce the mean CO_2 concentrations in the northern hemisphere if they included a tropical biotic source and a balancing northern mid-latitude sink, each of 1 Gt yr^{-1}. This agreement obtained using a different model indicates that the requirement for a strong mid-latitude sink in the northern hemisphere is a robust feature of the inversion.

5.4. *Northern hemisphere seasonality*

The double peak in the northern hemisphere release presumably indicates a decrease in respiration in mid-winter due to low temperature. This feature also appears in the inversions using the Eulerian transport fields and indeed it can even be seen in the inversions based on the one-dimensional diffusion model as shown in Fig. 2. The double peak behaviour is explicity included by Fung et al. (1983) and Pearman and Hyson (1986) in their respective models of biomass variation. It must be recalled that the seasonal cycle of CO_2 in the northern hemisphere is dominated by local sources and so is relatively insensitive to the details of the transport in the model. Thus the fact that the inversion produces the double peak is not a very strong confirmation of either the validity of the model or the accuracy of other details of the inversion.

5.5. *Tropical seasonality*

The strong seasonal source in the tropics, in zone 5 (11S to 0) and to a lesser extent in zone 4 is quite surprising. Such a variation is expected in neither the ocean exchange (see Fig. 4 of Pearman et al, 1983 for relevant modelling results) nor the natural cycle of the terrestrial biota.

In further examining the tropical seasonality the first possibility that must be considered is that this source is an artifact arising from inadequacies in the model. The seasonal cycles in the southern hemisphere have a significant contribution arising from the modulation of the interhemispheric gradient by a seasonally varying interhemispheric transport. A model with an inadequate representation of the interhemispheric transport might have to imply a spurious tropical seasonal source in order to give a consistent representation of southern hemisphere cycles. Indeed, this interpretation could possibly be applied to some of the spurious aspects of Fig. 4. However, evidence in favour of the validity of our deduction of a seasonal tropical source comes from the studies of CCl_3F by Enting and Mansbridge (1987a) using the present model. The model produced a seasonal cycle that agreed with observations at Samoa and Cape Grim. This consistency indicates that the seasonal aspects of the interhemispheric transport do not give spurious fluxes that could only be reconciled with observations by invoking additional unrealistic sources.

Additional evidence that some seasonal tropi-

cal source is really implied by the data comes from the qualititative agreement between Figs. 7 and 9. The Eulerian calculation differs mainly by dividing the seasonal source relatively evenly between zones 4 and 5. The seasonal tropical source seems to be a robust feature of the inversion.

As a tentative explanation, we propose that this seasonal component represents a consequence of biomass burning and that the peak in April represents the component that is burnt with the burning taking place in the drier months of the year as indicated by Crutzen (1987). The precise amounts of carbon involved will be a function of how the "base" level is defined. Fig. 9 of Enting and Mansbridge (1987a) suggests that about 0.7 Gt is released from zone 5 over about eight months of the year and about 0.2 Gt is released from zone 4 over four months.

As an example, Ayers and Gillett (1988) estimate that wild-fires and "controlled" burns in tropical Australia may produce up to 0.15 Gt of carbon from burning litter each year with an unknown contribution from burning standing biomass. The majority of this burning takes place early in the "dry" season. This component on its own would be sufficient to account for much of the seasonal peak found for zone 4. No great significance should be attached to this agreement because the severe smoothing applied to the concentration data suppresses high resolution information such as the distribution of the tropical peak between zones 4 and 5.

While much of the burning in tropical Australia is followed by regrowth with similar biomass, it seems possible that some of the larger seasonal release that we estimate for zone 5 corresponds to burning of cleared material from land that is being subjected to permanent (or long-term) deforestation. Houghton et al. (1985) have published estimates of deforestation. The four largest regions that they quote are Indonesia (0.192 Gt yr^{-1}), Columbia (0.123 Gt yr^{-1}) and the states of Para (0.129 Gt yr^{-1}) and Mato Grosso (0.117 Gt yr^{-1}) in Brazil. Except for Columbia, each of these regions is (at least predominantly) in the southern hemisphere (corresponding to our zone 5) and experiences its minimum rainfall in the middle of the year (Ratisbona, 1976; Snow, 1976; Sukanto, 1969). The appearance of the tropical clearing as a seasonal effect may explain the discrepancy between our results and those of Keeling and Heimann (1986). Their model calibration (Heimann and Keeling, 1986) specifically assumed no seasonal sources in the tropics. Also, as discussed in Section 3 above, the source deduction problem is sensitive to the errors arising from equating surface data to vertically averaged concentrations.

The interpretation of tropical CO_2 sources is complicated by the release of other carbon compounds both in natural cycles and in burning after deforestation (Crutzen, 1987). Some indication of the importance of such processes can be gained from a consideration of the CO budget because the most important oxidation pathways are via CO. The effect of having carbon released in compounds other than CO_2 is that a localized tropical carbon source would be seen as a widespread CO_2 source because the CO has time to disperse before being oxidized. Crutzen quotes estimates of 0.5 to 1 Gt of *CO* from biomass burning and about the same from oxidation of reactive hydrocarbons emitted from tropical forests. The two effects would give 0.4 to 0.8 Gt yr^{-1} *carbon* which is emitted from the tropics but appears in the CO_2 budget over a wider range of latitudes. The distortion that this causes to the apparent latitudinal distribution of CO_2 sources is limited by the fact that the oxidation of CO also peaks in the tropics because of the dependence of OH concentrations on solar radiation. The analysis is further complicated by the fact that oxidation of CO produces CO_2 throughout the whole volume of the troposphere. By assuming purely surface sources we have introduced an effective error in the model used for the inversion. Following our analysis of the sensitivity studies we would expect that such a misidentification of the vertical position of part of the source will have little effect on the large-scale features of the sources that we deduce but that local details may vary significantly.

6. Conclusions

Our results show that direct inversion of appropriately filtered CO_2 data can produce a set of estimates of CO_2 source strengths that exhibit a structure that is plausible on biological and geophysical grounds. The degree of resolution

that seems to be achievable corresponds to a meridional wave number of about 3 to 5. In formal terms, the limitation would seem to be in the CO_2 data, as though the model could support more precise inversions if better data were available. However, a closer consideration of the problem reveals that the distinction between model error and data is blurred. The limitation on the resolution achievable in the data is due to the fact that the actual CO_2 records reflect interannual and longitudianal variations. Thus the limitation on resolution could be regarded as due to the limitations of assuming a zonally-averaged strictly-periodic model.

The features that are apparent in the inversion are:

(i) oceanic sinks in the southern hemisphere primarily in mid-latitudes as recently suggested by Takahashi (1987);

(ii) the strong biotic cycle in the northern hemisphere with a local minimum in the winter CO_2 release presumably reflecting a temperature-related reduction in respiration;

(iii) the small seasonality in ocean CO_2 exchange at higher southern latitudes and the winter-spring peak in seasonal uptake in southern hemisphere temperate zones, indicating the possibility of the seasonal ocean CO_2 exchange being driven by the productivity of the marine biota;

(iv) a seasonally varying tropical source that may reflect forest clearing followed by burning during the drier months. In this connection we note that release of carbon from tropical forests in compounds other than CO_2 will mean that we have underestimated the net tropical carbon source.

We are currently seeking to refine these results by the use of isotopic information and by refinements of the model, the representation of the concentration data and the inversion procedure.

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